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EUROPEAN PHYSICAL SOCIETY
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NUCLEAR PHYSICS
Providing data for science and technology

ENVIRONMENTAL SCIENCE
Serving society by understanding
and monitoring environment

APPLICATIONS
of nuclear methods in space research,
materials science and quantum technology

INFRASTRUCTURE
Serving local and international partners
from science and industry

Foreword

ATOMKI was established 70 years ago for a specific reason. At that time, the Hungarian government recognized that the country needed nuclear competencies in the nuclear age. This has not changed since then. ATOMKI's mission is to conduct nuclear physics research and apply nuclear technology methods in various fields of science, primarily space research, materials science, environmental science, and heritage science. ATOMKI responds to global social challenges, particularly climate change, environmental pollution, and technical challenges, through the cross-sectoral application of nuclear technology.

Over the past 70 years, ATOMKI has gradually developed into an excellent research institute of the Hungarian Academy of Sciences, the accelerator center of Hungary, and a European laboratory for accelerator-based sciences. It is also an internationally known and recognized multidisciplinary research institute. In collaboration with leading European nuclear physics institutes, ATOMKI offers research opportunities to Hungarian and European research groups. Its world-class infrastructure and internationally recognized expertise enable these groups to conduct cutting-edge research at ATOMKI. Its researchers and their research proposals are welcomed at high-energy nuclear physics laboratories around the world.

The entrance to the Institute.

ATOMKI measures its success by its publications in high-level international journals. Over the past 10 years, the institute has doubled the quantity and quality of its publications, continuously improving its performance. On average, an international publication with ATOMKI contributions is published every working day. Eighty-five percent of the articles are written in international collaborations.

ATOMKI is an infrastructure-oriented institute. Its success is owed to infrastructure investments made over the past 10 years. Since 2016, the Tandetron, Heritage Science, Environmental Science Laboratories and a Radiocarbon Competence Center have been established within the framework of GINOP projects. Additionally, Geochronology, Surface Physics, and International Nuclear Physics activities have been supported.

Thanks to significant investments, ATOMKI is now home to 4 of Hungary's TOP50 research infrastructures. We actively participate in several major European Research Infrastructure Consortia, including ICOS (climate research) and E-RIHS (heritage science). ATOMKI is also involved in key international research infrastructure projects such as EURO-LABS in nuclear physics, EURO-PLANET in space research, and ChETEC-INFRA in nuclear astrophysics.

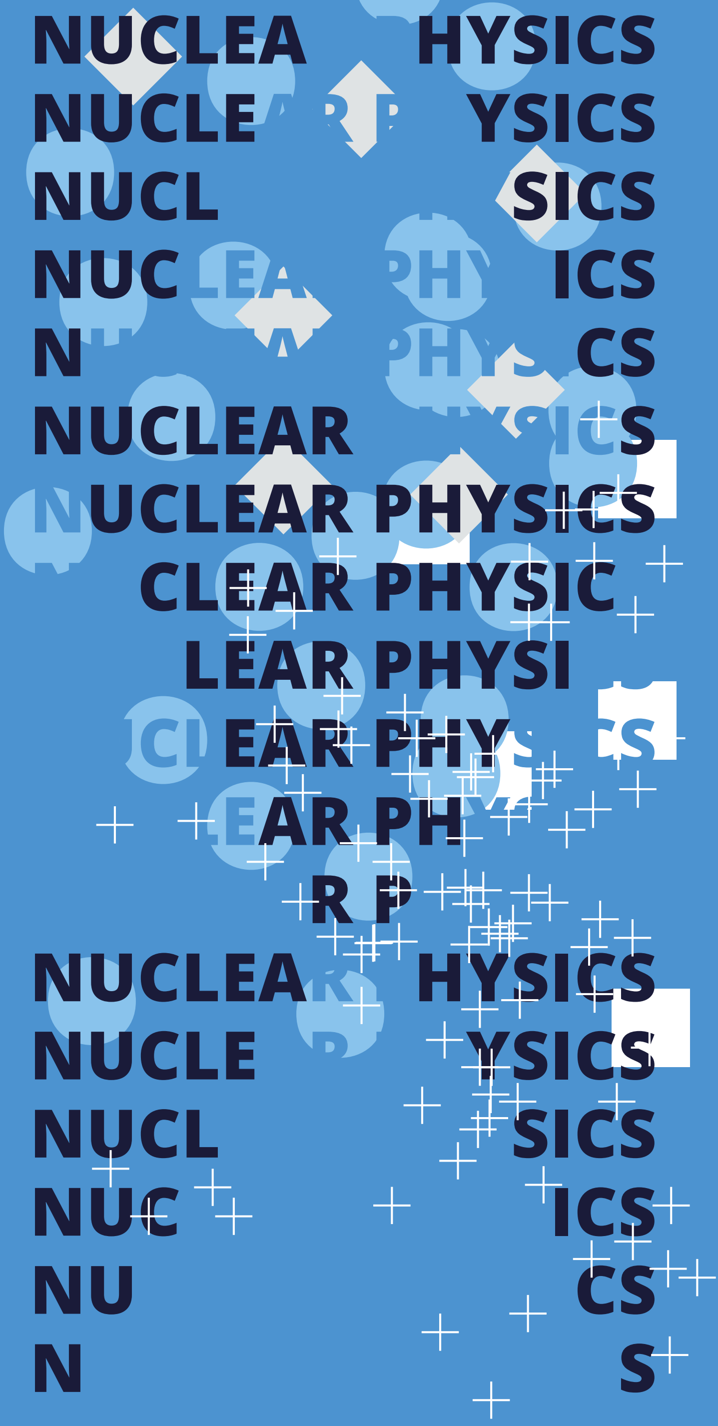
Due to these investments, ATOMKI has expanded its research portfolio over the past 10 years, becoming a multidisciplinary research institute. In addition to its traditional focus on nuclear physics, nuclear astrophysics, and nuclear technology, ATOMKI has expanded its role in environmental and heritage science, is building a space chemistry center, and has strengthened its materials science.

ATOMKI is an institute with a patina in its name yet new and Hungarian in its subject choice. Its research activities impact science, society, and technological development. ATOMKI has specific areas in which it can provide world-class infrastructural and technological services. It attracts international research groups and industrial partners who agree with ATOMKI's philosophy: Cooperation instead of competition.

Zsolt Dombrádi
director

NUCLEAR PHYSICS

Providing data for science and technology



- **NUCLEAR STRUCTURE STUDIES AT THE DRIP LINES**
- **QUANTUM CORRELATIONS AND ENTANGLEMENT IN NUCLEI**
- **INVESTIGATION OF THE EXPLOSIVE NUCLEOSYNTHESIS SCENARIOS**
- **NUCLEAR PHENOMENA RELATED TO EXOTIC SHAPES**
- **EXACT DESCRIPTION OF SHAPE PHASE TRANSITIONS IN NUCLEI**
- **EXPERIMENTAL STUDY OF STELLAR HYDROGEN BURNING REACTIONS**
- **DYNAMICAL SYMMETRIES IN NUCLEI**
- **NUCLEAR ASTROPHYSICS UNDERGROUND**
- **PARTICLE PHYSICS AT CERN AND BROOKHAVEN**
- **STUDY OF FUNDAMENTAL INTERACTIONS OF NATURE**
- **QUANTUM CHROMODYNAMICS ON THE LATTICE**

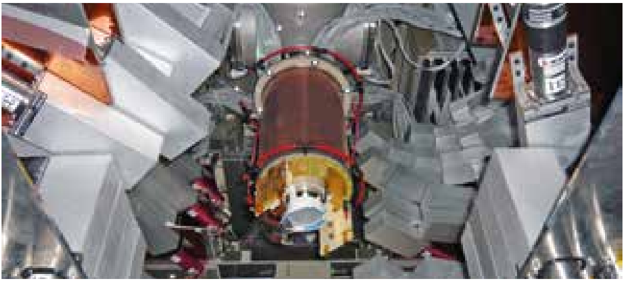
Nuclear Structure Studies at the Drip Lines

Searching for nuclear phenomena related to nuclei far from stability using radioactive ion beam facilities.

Nuclei, which make up 99.9% of the mass of atoms, are the building blocks of visible matter in the Universe, on Earth, and in us. Only about 300 isotopes are known to be stable, while more than 3000 nuclides are predicted to exist. As we move away from the valley of stability by adding neutrons or protons, we reach the limits of existence marked by the nucleon drip lines, beyond which no additional nucleons can be bound. Nuclei far from the stability line are expected to exhibit exotic properties due to the large imbalance of protons and neutrons.

According to the shell model, the fundamental model of atomic nuclei, nucleons occupy different energy levels, which are grouped into shells, similar to electron shells in atoms. Nuclei with fully filled shells of spherical shape and very rigid structures against excitations are milestones of theoretical calculations.

This project aims to identify exotic phenomena occurring in nuclear regions approaching the neutron or proton drip lines, such as the evolution of shell closures, the formation of islands with deformed shapes, and the appearance of shape coexistence. We put emphasis on the recently observed or predicted phenomena with experimental studies at the most advanced accelerator complexes, e. g. at RIKEN, GANIL, using our 25 years of experience in in-beam gamma-ray techniques combined with radioactive ion beams.

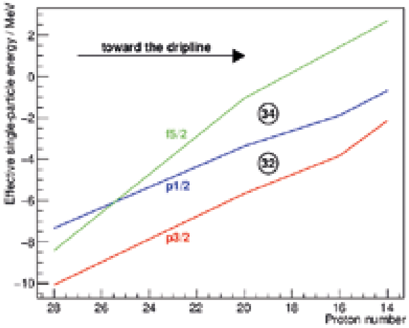


The DALI2+ gamma-ray detector system used in the in-beam experiments conducted at Radioactive Ion Beam Factory of RIKEN.

As users of the first generation of radioactive beam facilities at GANIL and at RIKEN since 2000, we have systematically studied the evolution of nucleon shells, observing the signs of disappearance of major shell closures at N=20, 28 and appearance of new shell closures at N=14, 16, 32, 34. We identified the cornerstone nuclei with fully filled shells and mapped the borders of island with deformed shapes in the A=30 and 40 mass region.

Recently, we tested the existence of the new shell closures at neutron numbers 32 and 34 by studying for the first time the low-lying excited states in ^{51}Ar. Our results showed a clear signature for the presence of significant shell closures at neutron numbers 32 and 34 in argon isotopes [1]. The appearance of new shell closures was theoretically explained by the tensor force, which should manifest itself as the neutron drip line is approached. By identifying the low-lying structure of ^{77}Cu, we proved the existence of the tensor force [2].

Our experimental research is carried out in international collaborations at large-scale facilities at ESFRI Roadmap institutes in Europe and Japan, Asia. These studies require high performance detectors for gamma rays and neutrons, which are built and operated by the international collaborations. Contribution to the procurement, installation and operation of the most important detectors at GSI-FAIR and GANIL in Europe and at RIKEN in Japan are also part of this project. Using the next generation of radioactive ion beams and the state-of-the-art detectors, we intend to explore the limits of nuclear stability and the nuclear properties near and beyond these limits.



Change in the effective single-particle orbitals at neutron number N = 32 as the proton number decreases toward the drip-line.

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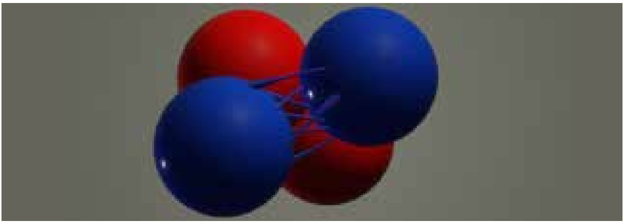
Quantum Correlations and Entanglement in Nuclei

The goal is the quantitative characterization of the correlation patterns that appear in the wave functions of atomic nuclei and the exploitation of this information in nuclear structure research.

Nowadays, one of the main directions of research is the investigation of entanglement and other quantum correlations. Since these phenomena do not possess classical analogy, they shed light on such consequences of quantum mechanics that go beyond the framework of classical physics. These correlations are significant from the point of view of the many-body problem because, according to experience, knowledge of the entanglement between subsystems provides opportunity to apply extremely effective approximation methods. Our goal is to describe and interpret the quantum information concepts in nuclear models.

We may obtain information that can support cutting-edge computations from the correlations observed in simple nuclear models and to expand the limits of nuclear structure computations by the application of new approximate methods.



Symbolic illustration of entanglement in a nucleus.

The theoretical discussion of nuclear structure is usually carried out in the framework of the quantum mechanical many-body problem by solving the time-independent Schrödinger equation. One of the major challenges is that the size of the model space increases exponentially from low to high mass nuclei, so that the solution of the many-body problem (even using supercomputers with the highest computational power) requires the use of significant approximations. Therefore, a central issue in this research area is the search for increasingly efficient approximation methods.

There is an important link between the efforts to efficiently approximate the states of a multibody system and the quantum correlations between the states, since when approximating a given wave function, it is usually most important to consider the components of the actual wave function that describe the largest degree of entanglement between the subsystems of the system under study. This observation is illustrated by the significant results obtained by the density matrix renormalization group method (DMRG method), based on the consideration of correlations between subsystems, in the study of multibody systems.

The subject of correlations in many-body systems is extremely diverse, and can include pure and mixed states, distinguishable and indistinguishable particles, classical and quantum correlations, mode and particle entanglement, and bipartite and multipartite entanglement.

The study of nuclear physics systems in terms of entanglement is a relatively young research area, and Atomki has recently become involved in this field. In addition to the quantitative characterisation of correlations and the identification of correlation patterns, there is a huge open area to explore the relationship between the quantities characterising correlations and traditional concepts in nuclear physics. Of particular interest, for example, is the question of how the approximate symmetries underlying phenomenological models are reflected in the quantities characterising correlations. To answer these questions, simple nuclear physics models provide an excellent starting point, for which numerical calculations covering all configurations of the state space can be performed and, in some cases, analytical results can be obtained |1-3].

In addition to the fundamental questions that can be addressed in the framework of simple nuclear models, another line of research is to push the limits of nuclear structure calculations, which essentially means exploiting the potential of the DMRG method in nuclear physics. This will be done in collaboration with the Wigner Research Centre for Physics, using the DMRG-Budapest software package. The software package provides a parallelised implementation of the DMRG method, which is used by several research groups worldwide to perform cutting-edge calculations.

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Investigation of the Explosive Nucleosynthesis Scenarios

About 50% of the isotopes heavier than iron are synthesized in explosive nucleosynthesis processes – such as r-, rp- and γ-processes. Experimental nuclear physics data are clearly necessary to interpret the modern astronomical observations and to obtain a more accurate picture of these nucleosynthesis scenarios.

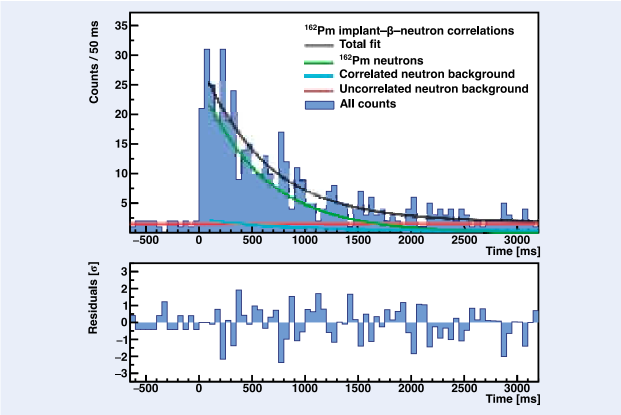
The astrophysical r-process is characterized by neutron densities exceeding 10^{26} neutrons/cm^3 and few GK temperatures. Under these conditions via series of neutron-capture reactions, very neutron-rich, short-lived isotopes, located close to the drip line can be formed.

When the neutron flux ceases, these isotopes decay toward the valley of stability and build up the neutron-rich stable isotopes. On the proton-rich side of the valley of stability there are about 35 nuclei which are separated from the path of the neutron capture processes. These, mostly even-even, isotopes between ^{74}Se and ^{196}Hg are the *p*-nuclei. It is generally accepted that the main stellar mechanism synthesizing the *p*-nuclei – the so-called *γ*-process – involves photodisintegration reactions. Furthermore, the *rp*-process may give a contribution to the abundances of the low-mass p-isotopes. For several decades, these nucleosynthesis processes were poorly known, since neither astronomical observations nor precise nuclear physics inputs were available.

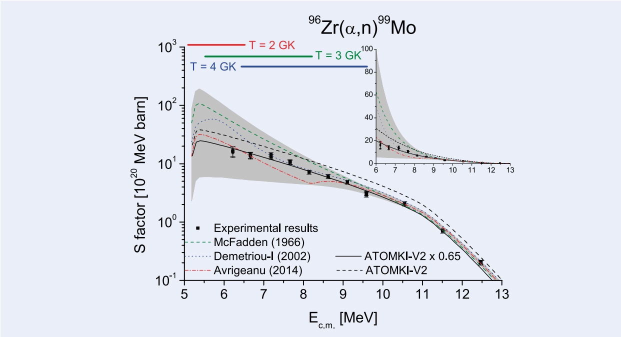
The parallel detection of gravitational waves and optical emission from merging neutron stars opened a new horizon for nuclear astrophysics. Now, after several decades of research, it is proved that about 50% of the stable isotopes heavier than iron (synthesized in the so-called *r*-process) could have originated from the explosion of neutron star mergers. On the other hand, studies of the composition of old, metal-poor stars at the edge of our galaxy point to supernovae as the site where heavy neutron-rich isotopes can be formed.

The interpretation of the astronomical observations requires precise knowledge on the nuclear properties of the isotopes produced during the explosion to update the nucleosynthesis models and explain the stellar abundance patterns.

Nowadays, the exotic nuclei lying on the paths of *r*- and *rp*-processes can be produced in radioactive beam factories with a yield suitable for experiments. The members of the Nuclear Astrophysics Group of the Institute for Nuclear Research contribute to a more precise scientific understanding of the explosive nuclear synthesis processes by measuring the beta decays of these proton/neutron-rich nuclei. Furthermore, the cross section measurement of charged particle induced and radiative capture reactions are needed for the network calculations used for nucleosynthesis simulations. These experiments are carried out using the cyclotron accelerator of ATOMKI.



Fit to implant-β-1n time correlation histograms for the decay of ^{162}Pm. The black line represents the total fit function, the red and blue lines show the correlated and uncorrelated background, respectively, and the green line indicates the parent decay.



Comparison of experimental and theoretical astrophysical S-factors of the ^{96}Zr(α,n)^{99}Mo reaction as a function of the energy (the inset shows the same data on a linear scale). The colored lines indicate the effective Gamow windows for ^{96}Zr(α,n)^{99}Mo at T = 2 GK, 3 GK, and 4 GK. The wide range of statistical modell predictions is indicated by the grayshaded area. Excellent agreement with χ2/N < 1 is only obtained for the ATOMKI-V2 calculation, scaled by a factor of 0.65 (full line).

Nuclear Phenomena Related to Exotic Shapes

Study of nuclear phenomena related to triaxially deformed shapes, as well as to shape coexistence, shape change, and extreme large deformations.

Atomic nucleus is a special quantum many body system which, has geometrical shape. This shape is plastic and affected by the nuclear excitation. Thus, there is a complicated interaction between excitation, intrinsic state and shape, leading to interesting phenomena.

The force binding nucleons into atomic nuclei is one of the four fundamental forces, yet it remains poorly understood. Understanding these forces is paramount for the development of nuclear models needed to predict the behavior of nuclear systems under conditions that cannot be directly accessed for measurement, ranging from nuclear reactor cores to astrophysical sites for nucleosynthesis. Thus, the studies of nuclear shapes enable stringent testing of nuclear models and will contribute to a better understanding of effective nucleon-nucleon interactions in atomic nuclei.

This project aims at studying nuclear phenomena related to triaxially deformed shapes, shape coexistence, shape change, and extreme large deformations. We put emphasis on the recently observed or predicted such phenomena with experimental studies at large scale facilities at ESFRI Roadmap institutes, e.g. GANIL, GSI, INFN-LNL, HIL, using our 50 years of experience in in-beam gamma-ray technique. While shapes of spherical or axial symmetry are common in nuclei, asymmetric shapes, although often predicted, are more difficult to find.

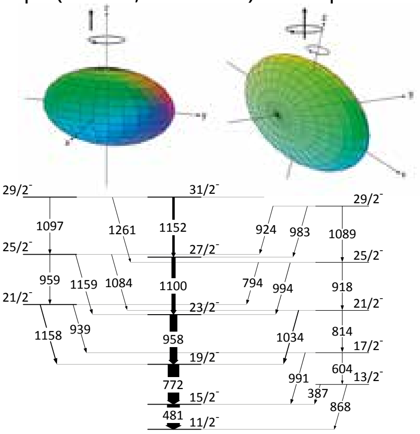
The DIAMANT detector system, designed and operated by ATOMKI, during the AGATA@GANIL campaign with the NEDA neutron detector array in the background.

Two recently predicted phenomena related to the triaxially deformed shape of the nucleus are at the focus of our studies, the wobbling motion and the chiral bands. Chiral bands are rotational bands being built on two intrinsic states which are mirror images of each other but they cannot be overlapped.

According to the most recent theoretical predictions, more than one configurations or both the ground and excited states of one configuration can be chiral, what emphasizes the role of the shape in the phenomenon. However, this could be shown only in few nuclei so far. Our group has shown the first case where both the ground and excited states of one configuration are chiral [1].

Nuclear wobbling motion has been theoretically predicted decades ago. However, experimental evidence for this phenomenon could only be found recently in a few nuclei. Our group has shown the first case in the A~100 mass region [2]. We plan to search for this phenomenon in the A~100 and A~130 regions, as well as to study if its properties depend on the particular region.

Our experimental research is carried out in middle-size international collaborations. These studies require special gamma- and charged-particle detectors, which are being built and operated in international collaborations. To contribute to the operation of the most important such detectors in Europe (AGATA, DIAMANT) is also part of this project.



Two types of rotations of the ^{105}Pd nucleus that has ellipsoidal triaxial shape, and the corresponding rotational bands.

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Exact Description of Shape Phase Transitions in Nuclei

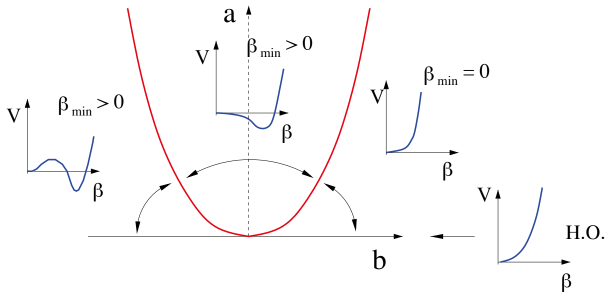
Some nuclear phenomena can be pictured as collective excitations around equilibrium nuclear shapes. Transitions from one such nuclear shape to another one have characteristic effect on the observables, and can be interpreted as shape phase transitions.

The Bohr Hamiltonian describes the dynamics of quadrupole-type surface excitations in nuclei. It relies on two key variables: $\beta \geq 0$, which quantifies the deviation of the nuclear surface from a spherical shape, and $\gamma \in [0, \pi/3]$, which characterizes its deviation from axial symmetry. The shape variables together with the three Euler angles describing the orientation of the nucleus constitute a five-dimensional system. All five variables appear in the kinetic term, while the potential $V(\beta,\gamma)$ depends only on the shape variables. The position of the potential minimum dictates the nuclear shape, which can be spherical, deformed prolate, deformed oblate, deformed triaxial, deformed γ-unstable, etc.

These equilibrium configurations can be interpreted as various shape phases. Changes in a control parameter in the Hamiltonian can produce a transition from one specific shape phase to another. The point of change is called a critical point and is characterized by a critical value of the control parameter. These critical-point solutions can be associated with various symmetries: E(5), X(5), X(3), Z(5) and Z(4). For example, the E(5) symmetry characterizes the critical point in the shape transition from spherical to deformed γ-unstable shapes.

The solutions of the Bohr Hamiltonian can be obtained by numerical calculations in general, however, there are a few potentials for which analytical solutions are available. This is the case when the potential is independent of the γ variable, so the problem reduces to a one-dimensional potential $V(\beta)$.

Among the solvable one-dimensional potentials, the sextic oscillator proposed by us turned out to be particularly useful in describing various nuclear shapes. Its flexible form can reproduce nuclear configurations with a spherical minimum, a deformed minimum, or both. Moreover, the transition between these different shape phases can be controlled analytically: besides the lowest few energy eigenvalues, the electromagnetic transition rates, e.g. the quadrupole B(E2) or monopole B(E0) ones can be calculated in closed form. A series of γ-unstable nuclei have been analysed in terms of this model in the Ru-Pd [1], the Pt-Os [2] and the Xe-Ba [3] regions. A key element of the analysis was comparing the relative strength of E2 transitions from excited 0^+ states to the first and second excited 2^+ states, because the model predicts different patterns for this quantity for the γ-unstable and the spherical shape phases. The isotopes ^{104}Ru, ^{108}Pd, ^{198}Pt, ^{134}Xe and ^{136}Ba have been identified as candidates for critical-point nuclei.



Various shape phases in the (a,b) parameter space of the model.

The model has been extended by incorporating the γ variable too using certain approximations. With this, a much wider class of nuclei and further critical point symmetries could be described. A recent review on the application of the sextic oscillator to describe nuclear shape phase transitions can be found in Ref. 4.

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Experimental Study of Stellar Hydrogen Burning Reactions

Exploiting the capabilities of the ATOMKI's Tandetron accelerator, a systematic study of low-energy proton-induced reactions relevant to the CNO cycles of stellar hydrogen burning is carried out. A cyclic activation technique is used, which provides the astrophysically important total reaction cross sections.

Hydrogen burning is the most important source of energy in stars and plays therefore a crucial role in the history of the Universe. Low-mass main sequence stars burn hydrogen into helium through the nuclear reactions of the so-called pp-chains. In more massive stars or in later stages of stellar evolution, however, other processes like the various CNO cycles are the main contributors for hydrogen burning. The nuclear reactions taking place in these cycles must be known in order to understand the energy generation and evolution of stars as well as the origin of the chemical elements building up our world.

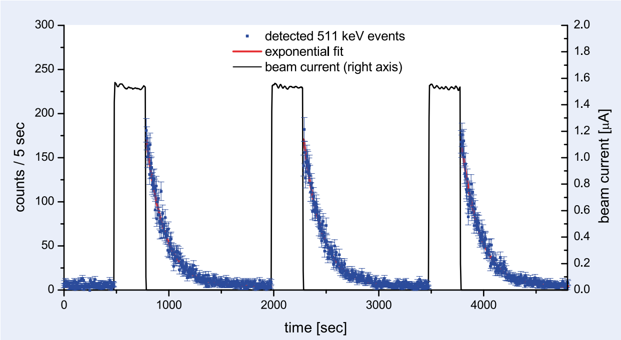
The astrophysically relevant energy range for the CNO cycle reactions is typically very low, of the order of a few tens of keV. Measuring the cross sections at such low energies is extremely difficult (or impossible). Therefore, the reactions need to be studied at somewhat higher energies with high precision in order to be able to extrapolate to low energies. A few hundred keV or 1-2 MeV is often the targeted energy range.

The Tandetron accelerator of ATOMKI is ideally suited for such studies as it provides proton beams with the required energy, intensity and stability. An intensive nuclear astrophysics program is thus being carried out at a beamline of the Tandetron accelerator dedicated to nuclear astrophysics research. The photo shows the end-station of this beamline with a gamma-detector and nuclear electronics.

The proton capture reactions in the CNO cycles often lead to radioactive isotopes which decay by positron emission with relatively short half-lives. In the subsequent positron annihilation, 511 keV γ-rays are produced. Their detection allows the reaction cross sections to be determined with the activation method. A target is first irradiated by a proton beam and the decay of the created reaction product is measured with a gamma-detector after the beam has been switched off.

This procedure is repeated several times, making up the so-called cyclic activation. A three-cycle part of such an activation is shown in the figure. The main advantage of the activation method is that the astrophysically important total cross section is provided and some typical sources of uncertainty can be avoided, such as the prompt beam-induced background or the angular distribution effect. In recent years, the proton capture cross sections of the ^{17}O, ^{14}N and ^{12}C isotopes were measured and our results obtained with the rarely used activation method provided important independent experimental data to the better understanding of the astrophysical processes. Stepping forward from the CNO cycles, our latest, presently ongoing project is the proton capture study on ^{29}Si, which is important for the nucleosynthesis in classical nova explosions.

Photo of the astrophysical end-station on
one of the Tandetron beamlines.



Example of a cyclic activation in the case of the ^{14}N + p reaction.
Three cycles are shown with the beam intensity, number of detected
511 keV γ-rays and the exponential fit of the latter.

Dynamical Symmetries in Nuclei

Symmetries govern the phenomena in Nature, as well as the basic laws. Atomic nuclei show many different symmetries. Here we consider one of them, discovered recently, which unifies the basic structure models.

The atomic nucleus consists of nucleons (i.e. protons and neutrons), usually containing many of them. Due to the complicated nature of the many-body problem we do not have an exact theory to account for all aspects of the structure. Rather, the fundamental models show the nucleus from one or another aspect, depending on their approach. (Just like in the ancient Indian parable of the blind men, who explore the elephant by touching it.)

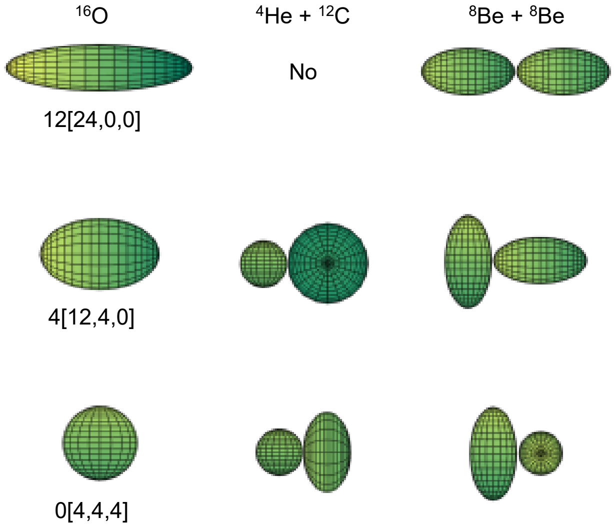
The collective model treats the nucleus as a microscopic liquid drop, which can rotate and vibrate. The shell model pictures it as a miniature atom (or solar system), while the cluster model considers it as a collection of smaller nuclei (like a bunch of grapes). What is the common part of these different pictures? (What does the elephant look like as a whole?)

It turned out in 1958 that the connection of the fundamental structure models is provided by a symmetry (called U(3) symmetry) for simple problems. Recently it was found [1] that a similar (though a bit more complicated U(3)×U(3)) symmetry, called multiconfigurational dynamical symmetry (MUSY), connects these basic models also for general problems.

In addition to providing us with an elegant doctrinal connection between the different theoretical frameworks, MUSY can give a unified description of different phenomena, e.g. it helps to determine the stable shapes of the nuclei, relate them to cluster configurations and reaction channels, as well as calculate their energies.

The figure shows the stable deformations of the ^{16}O nucleus together with some of their possible clusterizations.

The numbers characterize the U(3) symmetry. The figure illustrates the physical picture we associate to the collective and cluster models (while the shell model builds a bridge between them). In addition, there is a further connection, provided by the indistinguishable nature of the nucleons (called antisymmetrization).



This is one of the fundamental laws of Nature, revealed by quantum mechanics, to which we cannot associate any classical picture. As a consequence of the antisymmetrization, the shell, collective and cluster states (along a horizontal line of the figure) become identical.

MUSY has some interesting theoretical features, even beyond unifying the fundamental models of nuclear structure. E.g. it shows evidence for the two basic symmetry-breaking mechanisms: the spontaneous one, which results in asymmetric shape from symmetric interaction, and the dynamical one, which breaks the symmetry by interactions.

Since MUSY can describe different configurations in a wide energy and deformation region, it has a considerable predictive power. Though it is a young symmetry, some of its predictions have already been verified by experimental observation.

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Nuclear Astrophysics Underground

Measuring extremely low reaction cross sections requires special conditions. Beside the maximization of the reaction signal, the reduction of the detector background is of crucial importance. To reach the extremes an underground setting is inevitable.

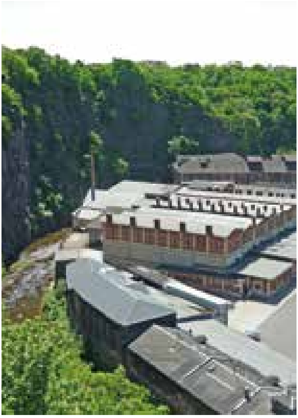
Nuclear astrophysics is dealing with reactions naturally occurring in stellar environments. These reactions are governing the life cycle of the stars, determining their energy generation, and the formation of the chemical elements in the Universe. Right after the Big Bang, the whole Universe was made of hydrogen and helium. The majority of the other chemical elements are formed inside the stars or during their violent destruction (nova or supernova explosions) mixing the material into the interstellar medium, finally into newly formed stellar systems.

To understand all these processes, it is inevitable to describe nuclear reactions. The energies at which these reactions occur in the stellar environments are very low, only the quantum mechanical tunneling effect makes them possible, however, with extremely low probability. To measure the reaction cross sections at those energies is often impossible, however, measuring as close to the relevant energy region as possible is mandatory to reduce the uncertainty of the extrapolations. In case of an experiment, the low reaction signal is often buried by the background in the detector(s).

To measure the extremely low cross section, it is inevitable to reduce the background events in the detector. These disturbing signals are caused mainly by the environmental radioactivity and by cosmic-ray induced events. While the former can be shielded by heavy material surrounding the detection system, the latter can be marginally mitigated by classic shielding. The cosmic-ray induced muons are the main source of the high energy detector background. On the surface of the Earth, 2 orders of magnitude background reduction can be achieved with so called muon veto detectors. These are additional elements in the detections system, making it not responsive when a muon penetrates through. However, this reduction is not enough for the purpose of nuclear astrophysics, and sometimes the caused additional detection dead time is also disturbing. The needed 4-5 orders of magnitude background reduction is achieved by setting up the experiment in deep underground.

One of such laboratory is the LNGS in Italy, below 1400 m of rock, which reduces the muon flux by 6 orders of magnitude, giving a possibility to measure such low cross sections, which are unparalleled elsewhere. The Nuclear astrophysics group of ATOMKI is a member of the LUNA collaboration (Laboratory for Underground Nuclear Astrophysics) for more than 30 years. LUNA operates a high current low energy accelerator in the heart of the Grans Sasso mountain, in the LNGS laboratory. During these years, the group was involved in many low energy reaction studies relevant for solar hydrogen and helium burning, which would not have been possible without the extremely low background conditions deep underground.

Recently, a higher energy accelerator is being installed at the same deep underground location, allowing the study of nuclear reaction of other burning stages of the stars directly at the relevant energy regions. More recently, the combination of the active shielding with shallower depths was investigated. It was proven that using an active veto a 100 m overburden is sufficient to reach similar background conditions as deep underground. In the recent years a shallow underground accelerator laboratory was built in Dresden, Germany, with a major contribution from the members of the nuclear astrophysics group of ATOMKI. The members of the group are regular visitors for experiments in the "Felsenkeller" laboratory. Beside others, reaction from the advanced burning stages of the stars and key helium burning reactions are investigated.



On the left, the "Corno Grande", the highest peak of the Apennines, below which the LUNA collaboration operates accelerators at deep underground. On the right, the old Felsenkeller brewery. In the tunnels dug into the rock behind the buildings operates the shallow underground accelerator laboratory.

Particle Physics at CERN and Brookhaven

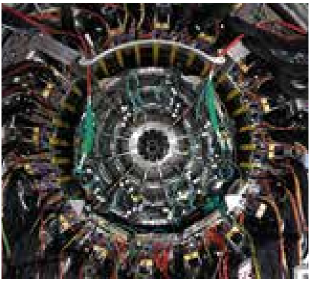
ATOMKI is involved in two significant experiments. One is with Brookhaven National Laboratory (BNL), the other with CERN.

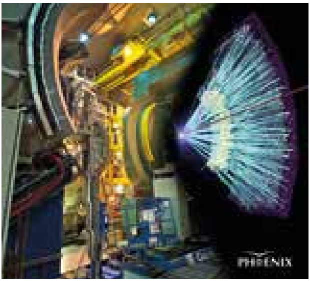
At the RHIC (Relativistic Heavy Ion Collider) accelerator heavy ion collisions are studied to understand the early Universe. The first detector was the PHENIX (2000-2016); its updgrade is the sPHENIX (2023-), the electron-Proton and Ion Collider (ePIC) will start its operation in 2029.

At BNL, the ATOMKI group studies the quark-gluon plasma. In particular, it focuses on light mesons and direct photon searches. High-energy heavy ion collisions produce a large number of photons that, due to their colour neutrality and relatively large mean free path, are able to escape from this quark-gluon plasma without reaction, giving us an account of the processes that take place during the collision. Data science algorithms were developed for the calibration and the physics analysis.

At ATOMKI a 72-channel monitoring system with a sampling rate of 10 Msps (Megasamples per second) per channel was developed for monitoring discharges/sparks in the Gas Electron Multipliers (GEM) of the sPHENIX Time Projection Chamber (TPC). Large fraction of the silicon photomultipliers (SiPMs) are using in the Electromagnetic Calorimeter (EMCAL) was studied with a SiPM tester designed and assembled at ATOMKI. Millions of SiPMs and large part of the front-end electronics will be tested and developed by ATOMKI in the next years.

The light meson and direct photon analysis will also be continued with the sPHENIX data.





TPC of the sPHENIX, PHENIX.

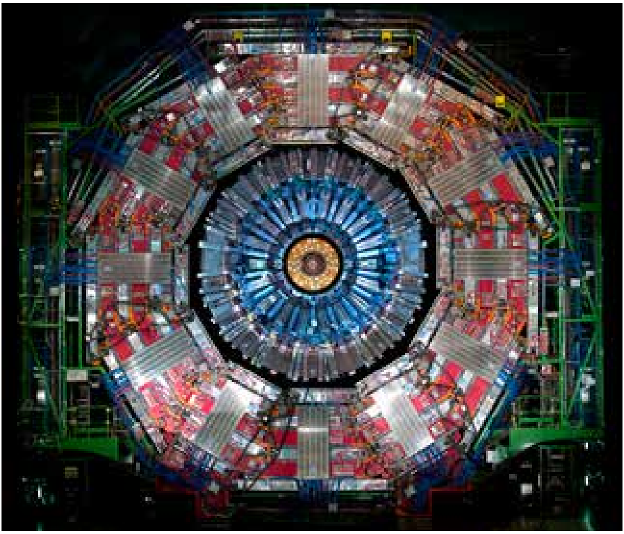
ATOMKI has joined three different hardware development and maintenance projects at the CMS (Compact Muon Solenoid) at CERN.

The CMS is a general-purpose detector at the LHC (Large Hadron Collider). It has a broad physics programme ranging from studying the Standard Model (including the Higgs boson) to searching for extra dimensions and particles that could make up dark matter.

In the very forward region of the CMS GEM detectors were installed capable of handling high particle collision rates. ATOMKI researchers work on the calibration of the GEM foils and assemble them with sensors for monitoring the temperature and the positions to ensure the proper operation of the detectors.

The position of the Drift Tube (DT) chambers at CMS is measured with a Muon Barrel Alignment System with an accuracy of 150-350 μm, developed and operated by ATOMKI researchers.

The main goal of the GEM detector is to detect muons during the operation of HL-LHC (High Luminosity LHC). ATOMKI researchers are involved in different upgrade projects by self-developed testing and monitoring set-ups, these solutions are also attractive for industrial partners.



Compact Muon Solenoid – CMS detector.

Study of Fundamental Interactions of Nature

We achieved groundbreaking results with the detection of a new light hypothetical particle at ATOMKI. Our publication was ranked in the top 5% of publications published in physics. The results have so far been confirmed by two research groups, and results of other groups are also expected soon.

In 2016, our group at ATOMKI observed a previously unknown anomaly in the decay of the 18.15 MeV state of the ^{8}Be nucleus by electron-positron internal pairing. Such an anomaly was explained by the creation and decay of a new particle with mass of ~17 MeV/c^2, and later named X17 in the literature. Recently we have observed similar anomalies also in the decay of ^{4}He and ^{12}C excited states which could be interpreted with the presence of the same X17 particle.

The newest version of our e^+e^- pair spectrometer is shown on the photo below. For each arm of the spectrometer we have two layers of high resolution Double-sided Silicon Strip Detectors (DSSD) to track the e^+ and e^- particles, and a big plastic scintillator to measure their energy.

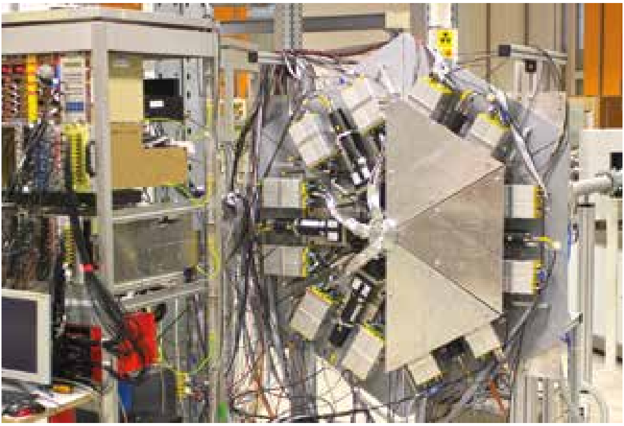
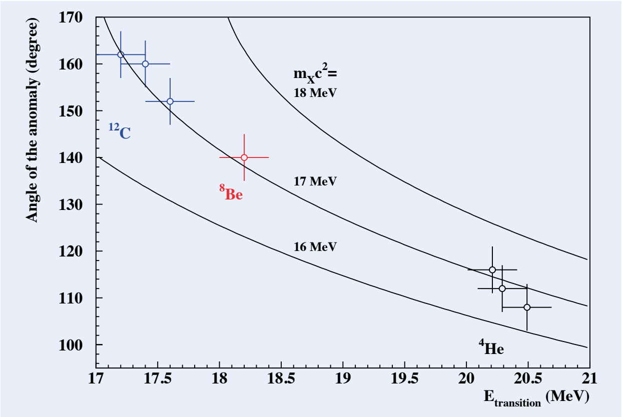


Photo of the e^+e^- pair spectrometer we are planning to use in the future for studying the properties of the X17 particle.

The excitation energy of the nucleus is well defined in all cases. This energy is used to create a new particle, and the rest gives kinetic energy for the created particle.

The larger the kinetic energy, the smaller the opening angle between the $e^+ e^-$ pairs, according to the formulas derived for the two particle decay of a moving particle. The results of such calculations are also shown below.



Two-body e^+e^- decay kinematics of the hypothetical X17 particle. The angle of the observed anomaly is shown as a function of the kinetic energy of the X17 particle created in different nuclear reactions, as labelled in the figure.

The full curves are calculated by assuming m_0c^2 = 16, 17 and 18 MeV for the rest mass of the decaying particle. All our measurements so far obtained for ^{12}C, ^{8}Be and ^{4}He are shown also in the above graph with circles and error bars follow well the simple theoretical line calculated for m_0c^2 = 17 MeV. Providing strong evidence for all results having been caused by the same X17 particle.

In the coming years, we are going to supplement the e^+e^- pair spectrometer with more telescopes, 3 in upstream and 3 in downstream directions, to measure the angular momentum of the X17 particle when it is emitted. With this upgrade, we will be able to determine the spin and parity of the X17 particle. We are going to measure the gamma-gamma-decay of the X17 also to learn more about the nature of this interesting particle.

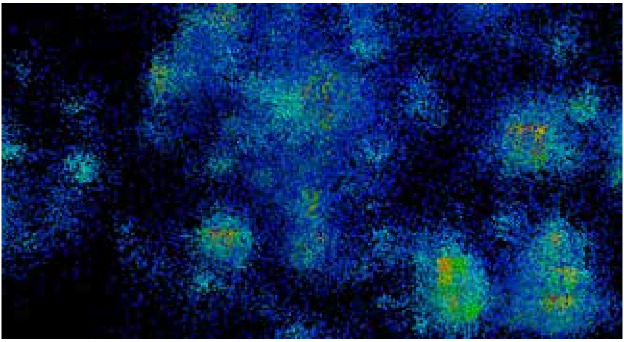
Such a new particle may create a connection with dark matter that is the reason why our experimental results created great international interest. In the future, we plan to investigate the properties of this particle with the help of the recently developed synergy of high-energy physics (HEP) and nuclear physics (NP), both at home and in large international collaborations. Today, the research of the X17 particle has become a new research topic worldwide.

Quantum Chromodynamics on the Lattice

We use lattice field theory to study strongly interacting systems in extreme conditions. Our results are relevant for a better understanding of heavy-ion collision experiments and the early Universe.

The fundamental particles, quarks, making up most of the visible matter around us, are bound into neutrons and protons by the strong interaction, mediated by gluons. Quantum chromodynamics (QCD), the theory of strong interactions is already 50 years old, but we still lack a full understanding of all of its consequences. It is particularly challenging to understand strongly interacting systems under extreme conditions, ones occurring in heavy-ion collision experiments, in the early universe and in neutron stars.

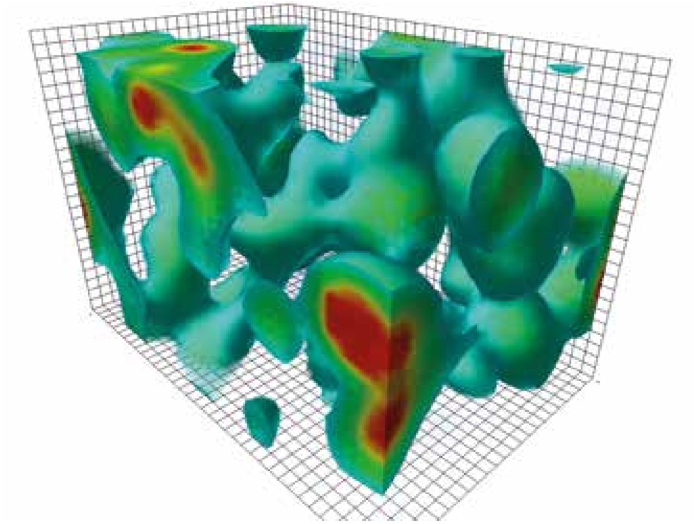
The only possibility to study these systems theoretically, starting from first principles, is by using lattice field theory, providing not only a proper mathematical framework to define QCD, but also a powerful numerical tool to explore its physical consequences. A large fraction of the computer time on the most powerful supercomputers in the world are devoted to state-of-the-art lattice QCD calculations. At the same time smaller scale calculations are carried out to obtain a more detailed understanding of the underlying physics, an understanding that can also help in developing more efficient algorithms for the largest scale computations. Using a small cluster of graphics card (GPU) based computers at ATOMKI we work mostly in this direction.



Wave function of a low-lying quark state in QCD at high temperature.

Recently we showed that special configurations of the gluon field, so-called instantons play a major role in shaping the transition of strongly interacting matter to the high temperature quark-gluon plasma phase. Even at high temperature each instanton hosts a quark state of extremely low energy, a state that would not be present without the instantons. These lowest quark states determine how the most important global symmetries of QCD, the chiral symmetries are realised at high temperature. Inspired by lattice simulation data, we constructed a simple model that describes the low-energy quark states and can be used to settle a decade-old controversy about the realisation of the U(1) chiral symmetry in the quark-gluon plasma [1]. Our results can have interesting consequences for the nature of the transition.

Some details of the transition, however, are not captured by our model, and need to be addressed by direct lattice QCD simulations. A major obstacle here is that to resolve the fine details of the low-energy quark spectrum, one needs a lattice quark discretisation that is both extremely expensive in computing power and technically challenging. We are presently working on this problem in collaboration with a group at the University of Wuppertal and the Forschungszentrum Jülich.



Typical instanton configuration of the gluon field
(courtesy of Derek Leinweber, University of Adelaide).

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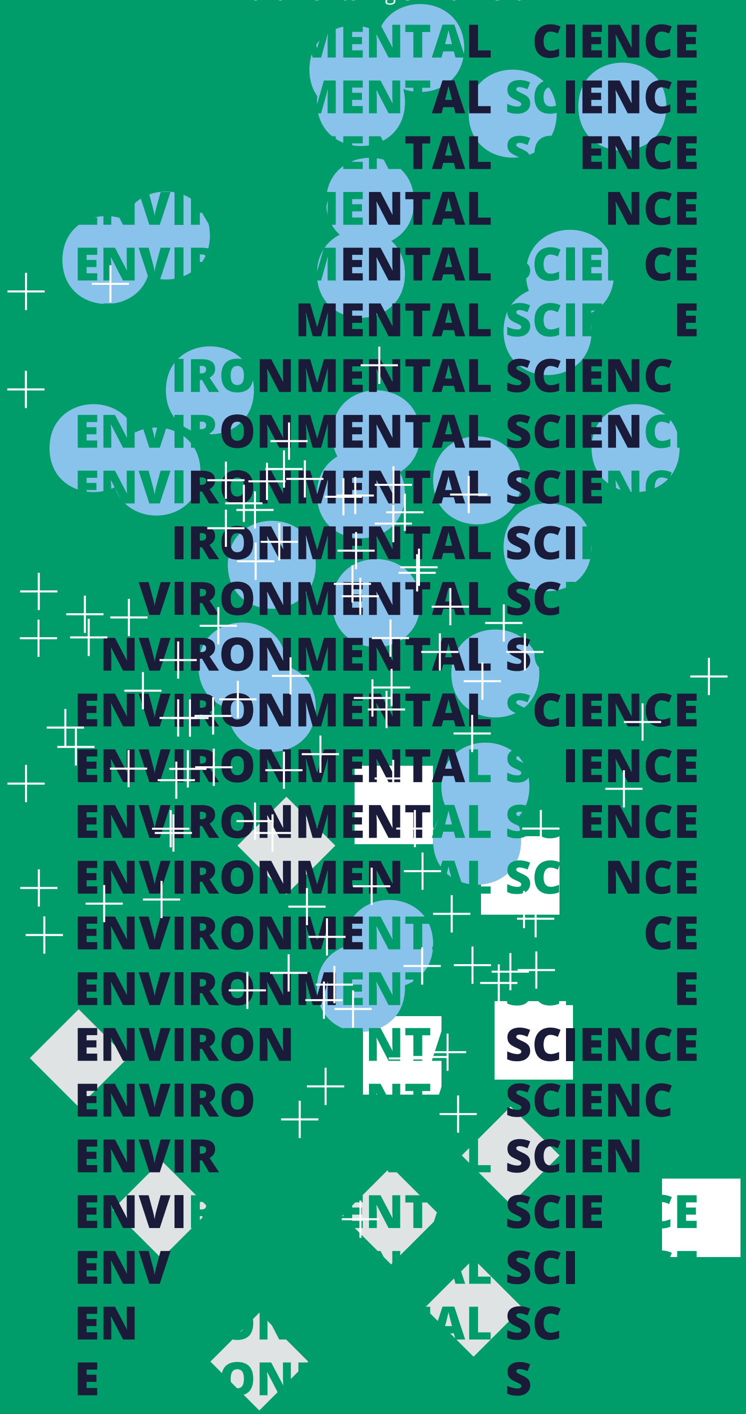
ENVIRONMENTAL SCIENCE

Serving society by understanding
and monitoring environment



- **ATMOSPHERIC AEROSOL RESEARCH**
- **GREENHOUSE GAS BUDGET OF THE ATMOSPHERE**
- **ISOTOPE HYDROLOGY**
- **CARBON CYCLE RESEARCH AND RADIOCARBON DATING**
- **HERITAGE SCIENCE**
- **PALAEOCLIMATE RESEARCH**
- **GEOCHRONOLOGY**
- **ENVIRONMENTAL GEOCHEMISTRY**
- **DETERMINATION OF REGIONAL GREENHOUSE GAS EMISSIONS**
- **INDUSTRIAL APPLICATIONS OF ^{14}C**

Atmospheric Aerosol Research

Characterization of atmospheric particulate matter pollution and its effects on human health, the environment, and the climate.

Atmospheric Particulate Matter (APM) pollution is one of the most severe environmental problems in densely populated areas of the world. Atmospheric aerosols play an important role in the energy balance of the Earth; they have a huge impact on the natural and built environment and are associated with many adverse health effects, including lung, cardiovascular, and cerebrovascular diseases.

At ATOMKI, we have been carrying out atmospheric aerosol research for three decades using accelerator-based ion beam analytical methods. In this time, we have created a continuously growing database that contains concentrations and elemental compositions of PM10 and PM2.5 characteristic to the region. This unique, long-term database forms the basis of our research.

One of the main directions of our research activity is the complex physical and chemical characterization of urban aerosol pollution and the identification of pollution sources using modern sampling, analytical, and statistical methods and models. We determine short- and long-term changes and trends in pollution sources, assess the impact of meteorological parameters, human activities, and natural processes, distinguish pollution from local, regional, and long-term transport, and identify geographical source areas.

SEM image of aerosol particles.

PIXE measurement of aerosol samples at the external beamline of the ATOMKI Tandetron accelerator.

Since 90% of human exposure to aerosols originates from indoor sources, another direction of research is the assessment of indoor aerosol pollution (including in schools, kindergartens, homes, workplaces, public transport, etc.).

The research contributes to the understanding of the basic properties of atmospheric aerosols and aerosol pollution sources. The complex characterization of air pollution sources provides essential information for authorities as well as for society, which serves as the basis for effective mitigation strategies.

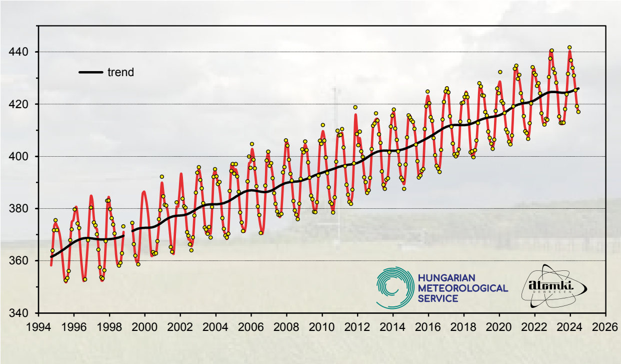
Part of the activity is carried out in the frame of regional and inter-regional projects of the International Atomic Energy Agency (IAEA), and we have joined the EU JRC FAIRMODE (Forum for Air Quality Modelling) project, ensuring that significant new results are produced at international level, too.

Greenhouse Gas Budget of the Atmosphere

Operation of a greenhouse gas monitoring site for climate research; participation in the pan-European Integrated Carbon Observation System (ICOS); co-ordination of the ICOS-Hungary research consortium.

The global climate change primarily caused by the accumulation of greenhouse gases is one of the biggest challenges humankind faces today. Mitigating the potentially severe impacts on human society requires profound political and economic decisions on both global and national levels, for which a sound scientific basis is essential. Science needs to understand the sources, sinks, and atmospheric processes of greenhouse gases in the atmosphere, as well as all the factors that affect them. Shortly: to understand the greenhouse gas budget of the atmosphere. Isotope compositions of greenhouse gases help clarify the anthropogenic contribution to the greenhouse gas content of the atmosphere.

The International Radiocarbon AMS Competence and Training Center (INTERACT) of ATOMKI has a long tradition of studying the global carbon cycle, including the atmospheric processes of carbon-containing greenhouse gases (carbon dioxide, methane). INTERACT and its predecessor have been measuring the radiocarbon content of atmospheric carbon dioxide at Hegyhátsál tall-tower greenhouse gas monitoring station since 2008. The operation of the station was taken over from its former operator, Hungarian Meteorological Service, in 2020. Based on this research-level monitoring site and the related scientific background, Hungary joined the pan-European Integrated Carbon Observation System (ICOS), a European Research Infrastructure Consortium (ERIC) on January 1, 2022.



Trend and seasonal variation of atmospheric carbon dioxide concentration at Hegyhátsál based on the measurements performed by the Hungarian Meteorological Service and ATOMKI.

The atmospheric concentration of carbon dioxide has been measured at a tall-tower greenhouse gas monitoring station in the vicinity of Hegyhátsál village since 1993. The measurements are performed at four elevations (10 m, 50 m, 82 m, 115 m) along a TV/radio transmitter tower to gain information on the vertical distribution of this important greenhouse gas. In addition to the concentration measurements, the biosphere-atmosphere exchange of carbon dioxide is also monitored in cooperation with Eötvös Loránd University. Worldwide compatibility of the measurements is assured by using calibration standards prepared and certified by the Central Calibration Laboratory of the World Meteorological Organization, hosted by the National Oceanic and Atmospheric Administration of the United States of America. Radiocarbon content of carbon dioxide indicating the fossil fuel origin is determined at the laboratory of INTERACT ATOMKI.

In addition to carbon dioxide, the concentration of methane, the second most important greenhouse gas of anthropogenic origin, has been measured since 2006. An open, and highly important scientific question is how much more methane is released nowadays from natural sources disturbed by global climate change than before the industrial revolution. This strong natural feedback between climate change and the emission of a potent greenhouse gas might undermine our mitigation efforts. Both the concentrations of carbon dioxide and methane in the atmosphere are steadily increasing urging significant emission reduction in the short term.

Isotope Hydrology

Using isotope hydrology reveals water paths in the short and long-term processes.

Isotope hydrology plays a vital role in water cycle research by providing valuable insights into various aspects of the Earth's hydrological system Here's how isotope hydrology contributes to the study of the water cycle: tracking water movement, quantifying precipitation sources, groundwater recharge studies, climate change research, hydrological modeling, and solar cycle research.

Isotope hydrology contributes to climate change studies by providing data on past climate conditions. Isotopic analysis of ice cores, sediment records, and other natural archives can reveal historical climate variations, helping reconstruct climate patterns over long-time scales.

Precipitation is a fundamental component of the water cycle. Isotope analysis of precipitation allows identifying the moisture sources that contribute to rainfall in a particular region. This information is critical for understanding the origins of precipitation and its variability.

In summary, isotope hydrology is a powerful tool for advancing our understanding of the water cycle. By analyzing the isotopic composition of water samples from various sources and stages of the cycle, we can uncover critical information about water movement, sources, and behavior.

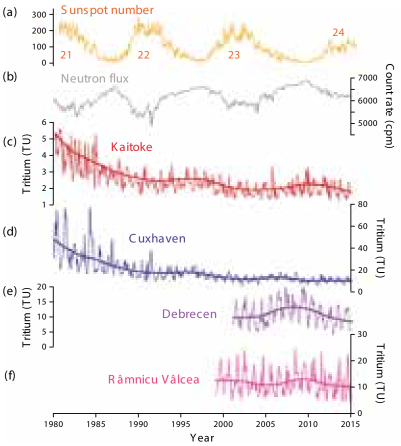
Groundwater sampling for palaeoclimate research
in the Tadla Basin, Morocco.

This knowledge is essential for effective water resource management, climate research, and addressing water-related challenges in a changing world.

The use of environmental isotopes is a powerful tool that enables us to analyze the patterns of spatially and temporally variable phenomena, providing valuable insights into the dynamics of natural systems and environmental processes.

Understanding the connection between the solar cycle and tritium concentration in precipitation is a prime example of how environmental isotopes allow us to investigate the intricate relationship between solar activity and the Earth's hydrological cycle, offering insights into how cosmic ray variations during solar cycles impact tritium levels.

Time series of environmental tracers both in the groundwater recharge and discharge provide important insights into how a karst water system works. By analyzing the fluctuations in tritium concentration in precipitation over extended periods and correlating it with corresponding changes in karst spring discharge, we can uncover valuable information about groundwater flow dynamics and storage within karst aquifers. In addition, water isotopes serve as a valuable tool for characterizing the intricate microphysical processes occurring within clouds and uncovering the moisture source regions in a given area.



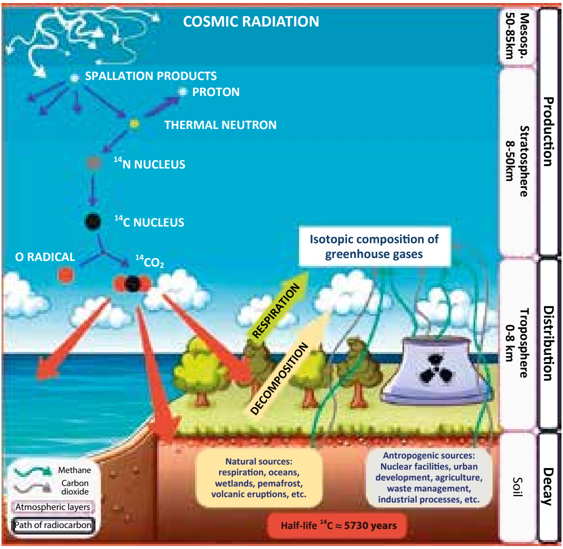
Connection between the solar cycle and the cosmogenic tritium in precipitation. Time series of (a) sunspot numbers, the number of the solar cycle is also indicated; (b) neutron count rate (Oulu, Finland); (c–f) tritium time series with spline average trends in four selected location (Kaitoke, New Zealand; Cuxhaven, Germany; Debrecen, Hungary; Râmnicu Vâlcea, Romania).

Carbon Cycle Research and Radiocarbon Dating

Unlocking the Carbon Cycle with Isotope Research: understanding how carbon transfers between the atmosphere, oceans, and land is crucial for assessing climate change, identifying pollution sources, and examining past environmental shifts.

Carbon is the foundation of life on Earth, cycling through the atmosphere, biosphere, and oceans in complex natural processes. Among its isotopes, carbon-14 (^{14}C) is unique – being radioactive, it serves both as a chronometer and tracer of carbon movements. ^{14}C is produced in the upper atmosphere when cosmic rays interact with nitrogen atoms. It quickly oxidizes into carbon dioxide (CO_2), spreading throughout the biosphere and integrating into all living organisms. Once an organism dies, it stops absorbing new ^{14}C, and the isotope begins its predictable decay (with a half-life of 5,730 years).

This principle underlies radiocarbon dating, enabling scientists to determine the age of organic materials up to 50,000 years old. However, ^{14}C serves as more than just a dating tool—it offers invaluable insights into both natural and human-induced carbon fluxes.



Global Carbon Cycle and ^{14}C Fluxes – A visual representation of how ^{14}C moves between the atmosphere, biosphere, and oceans.

ATOMKI's Contribution: Cutting-Edge ^{14}C Research

The International Radiocarbon AMS Competence and Training Center (INTERACT) of ATOMKI, Debrecen, is Hungary's leading radiocarbon research center, applying ^{14}C and other C-isotopes to diverse fields beyond dating.

Our work spans:

Radiocarbon dating for archelogy and environmental research
We determine the age of ancient artifacts, bones, and wooden structures, revealing historical events and cultural transitions. From medieval settlements to prehistoric tools, our precise ^{14}C measurements help reconstruct the past [1, 2].

Geology and Climate Reconstruction
Our research on peat bogs, sediments, and tree rings decipher past climate changes. We contribute to understanding long-term environmental shifts through carbon cycle modeling [3, 4].

Hydrology and Water Systems
Using ^{14}C and other isotopes, we trace groundwater movement and recharge rates, distinguishing between young and fossil waters—vital for sustainable water resource management [5].

Why Radiocarbon Research Matters
At ATOMKI, we expand the boundaries of ^{14}C science, connecting the dynamics of the carbon cycle from the past to the present and future. Whether revealing the secrets of ancient civilizations, tracking climate change, or validating sustainable materials, our research ensures that radiocarbon remains an essential tool for both science and society [6].

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[6] A.J.T. Jull, et al., Nature Communications **12** (2021) 712

Heritage Science

The aim of heritage science is to enhance the understanding, care, and sustainable use of heritage. As a multidisciplinary domain, heritage science interconnects knowledge and methodologies to address key scientific questions in the field.

The tangible memories of our heritage are characterized not only by their stylistic features but also by their materials and physical properties, from which new knowledge of historical significance can be extracted with appropriate interpretation.

The Heritage Science Research Group is embedded in the European heritage science landscape as an access provider to its infrastructure and expertise in material characterization and carbon dating. Large-scale facilities are complemented with various imaging and analytical tools for a thorough investigation of art and archaeological objects.

Our laboratories provide information on the structure, material composition, and age of archaeological and museum objects over a wide range of scales using scientific methods, dating, and equipment that allows non-destructive material analysis at the microscopic level.

Micro- and nanoscale imaging, measuring the concentration of elements and isotopes, and identifying chemical compounds and mineral phases can help to reveal the origin, production technology, age, raw materials and state of preservation of objects, as well as the way our ancestors lived.

Raman spectroscopic analysis of a turquoise covered Aztec wooden mask (Museum of Ethnography, Budapest).

Heritage studies is a multidisciplinary field, and our research seeks to answer questions raised by museum professionals and archaeologists. An ion beam analytical setup, installed at the beamlines of the ATOMKI Tandetron accelerator, serves to determine the concentration and distribution of elements both in vacuum and in-air (for larger or sensitive artefacts) with high lateral resolution.

A collection of analytical and imaging tools (3D digital microscope, micro-XRF, Raman microscope, variable pressure electron microscope, etc.) provides complementary information on the structure and composition of the objects. Other ATOMKI infrastructure can also be recruited if need be. The age of objects and jewellery made of organic (e.g. bone, tooth, antler) or inorganic (e.g. shell) carbonaceous materials is determined using the C-14 method, which often also provides the date of the site itself. By measuring carbon, nitrogen and sulphur stable isotopes, we can obtain information on feeding habits or migratory processes. Microfossil analysis of human and animal dental calculus remains can also help us to clarify the history of food and plant cultivation. The hydrogen and oxygen stable isotopes in the inorganic apatite fraction provide evidence of environmental factors, while strontium can be used to trace human migration or, in the case of an object, its place of origin. In addition to joint research with our partners, we carry out methodological research, including optimising measurements and data evaluation for the groups of materials we study, reducing the limit of detection, increasing accuracy, exploring new areas, and, very importantly in this field, defining the safe limits of materials testing methods.

PIXE analysis of a decorated armband, found in the vicinity of Dunavecse (Hungarian National Museum).

Palaeoclimate Research

Palaeoclimatology explores and characterises the palaeoenvironment by studying different archives, indicators, and integrated scientific fields using complementary techniques. In ATOMKI we use biogeochemical and isotopic evidence of organic and inorganic climate archives to reconstruct past environments mainly in the Carpathian-Pannonian-Dinaric region. Our results feed the climate models with local data helping to predict the future.

Water and food supply, essential for life on the Earth, are threatened. The current, climatically strongly influenced environmental conditions and the driving forces behind them can be learned more deeply if studied on a larger scale than a few generations. This is why it is necessary to go back to the past. The paleoclimate research of ATOMKI aims to meet this global challenge of climate change by analysing local and regional interpretations of changes in the paleoclimate making climate models more precise with further data. Science can draw the attention of natural resource management and public policy to priorities and help focus on them to make problem-solving more effective.

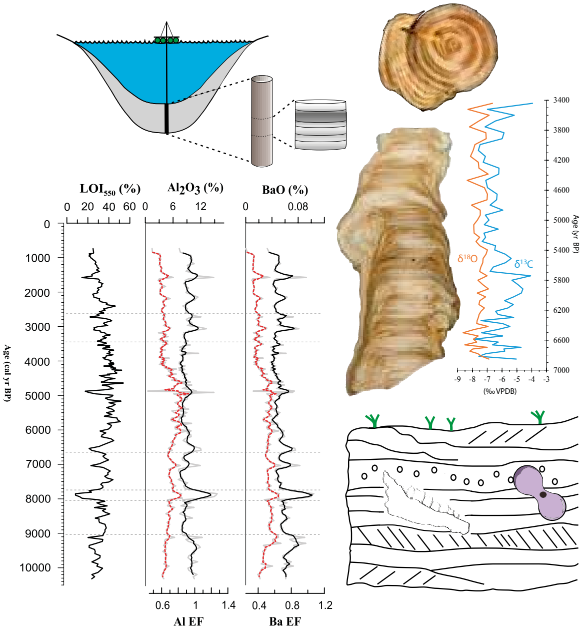
The European Regional Development Fund and the Hungarian government reinforced paleoclimate research at ATOMKI in 2016.

Glacier ice, glacial lake sediments, landforms and geological formations all provide valuable information about past climate events (Gornergletscher, Switzerland, photo by Marjan Temovski).

PALAEOCLIMATOLOGY RESEARCH GROUP

This field relies on multidisciplinary experts and exploits ATOMKI's unique instrumentation and techniques of isotope geochemistry and hydrology, geophysics, climatology, ecology, palaeontology, dendrochronology, environmental archaeology, and engineering.

We combine field, experimental, and modelling studies with advanced laboratory techniques. Methods include different types of sampling, geochemical analyses, microstructure analysis, micro-, and macrofossil analyses, dendrochronology, radiocarbon dating, uranium-thorium dating, microscopy, mass spectrometry techniques: LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry), MC-ICP-MS (Multicollector Inductively Coupled Plasma Mass Spectrometry) measurements for additional stable isotope measurements on various environmental samples. Our work is important also because these sampling and analytical skills are all suitable for examining and evaluating the recent state of the environment.



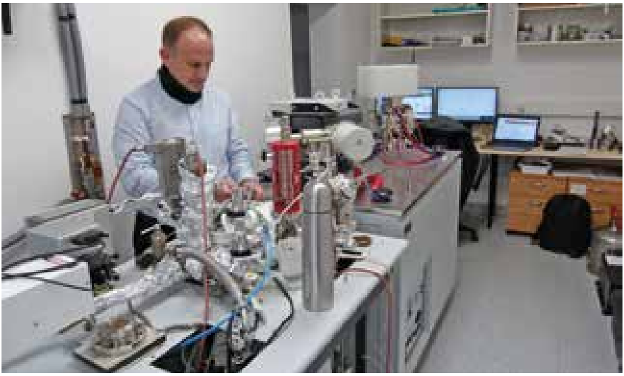
Various methods and archives of our paleoenvironmental studies: schematic figure of sampling with the position of a glacial lake sediment core and its geochemical data; tree rings; speleothem with its isotope composition; loess section with micro- and macrofossils.

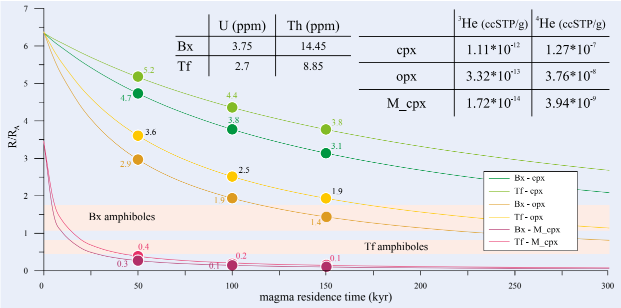
Geochronology

The main interest of our group is dating of rocks using the K/Ar, $^{39}Ar/^{40}Ar$, (U-Th)/He and fission track methods. Furthermore,we analyze noble gas isotopes in inclusions hosted by rock forming, alteration and ore minerals.

Precise dating of rock forming-, ore- and alteration minerals is an essential input to a wide variety of geological research projects, including raw material- and hydrocarbon exploration, as well as in fundamental research. With the applied geochronological techniques, we can cover the whole geological age spectra from the formation of the Earth, until the most recent times. Combination of the various techniques provides us an excellent opportunity to understand the cooling history of magmatic and metamorphic complexes from relatively high (500-600°C) to low (50-100°C) temperatures. We are particularly interested in the dating of diagenetic and anchimetamorphic alteration of sedimentary sequences that are targets for hydrocarbon exploration and nuclear waste disposal.

Since the establishment of the lab in 1978, we have analyzed more than 9000 samples from all continents, including Antarctica. The vast majority of rocks in the Carpathian-Pannonian-Dinaric region has also been dated in our lab, mainly using the K/Ar dating technique. The scientific collaborations of the lab extend to all Hungarian and many foreign universities, research centers and companies. A new Argus VI© multicollector, and a MAP 215-50 single collector mass spectrometers guarantee us the high precision and high accuracy in the analysis of Ar isotopes.





The evolution of R/R_A values of piroxene and amphibole samples from the Ciomadul volcanic complex through time with the different starting He isotopic compositions.

He isotopes for (U-Th)/He dating are measured with a Multimass type noble gas mass spectrometer. Extraction of noble gases is carried out by laser ablation, radio-frequency and resistance heating; the gas cleaning systems are home-made and are equipped with high quality VAT valves and SAES© getters.

In the field of fission track dating, our lab has taken the first steps towards the development of fission counting by machine learning and artificial intelligence.

Analysis of noble gases (He, Ne, Ar) entrapped in melt and fluid inclusions of various minerals gives an additional tool to the geologist to unravel their origin, pre-, and post-crystallization history. It is particularly important in the case of some rare rock types, such as carbonatites, lamprophyres and other alkaline rocks that host strategic elements (rare-earth elements, Nb, Ta).

Therefore, the research portfolio of our lab has been extended to the complex analysis of alkaline rocks with special attention to their noble gases. We have been studying carbonatites from India, the USA, Uganda, Czech Republic and Greenland.

Our studies on the Ciamodul volcano (Romania) proved that the combination of geochronological data with the noble gas isotope record of magmatic rocks can provide additional unique observations on magma evolution.

As the representatives of the Earth Sciences (especially geology) in the ATOMKI, beyond the geochronology and noble gas analysis we are performing many other mineralogical, volcanological and economic geology research using other conventional physical, petrographic and geochemical methods.

Environmental Geochemistry

Using isotope geochemistry to understand the changes in environmental processes.

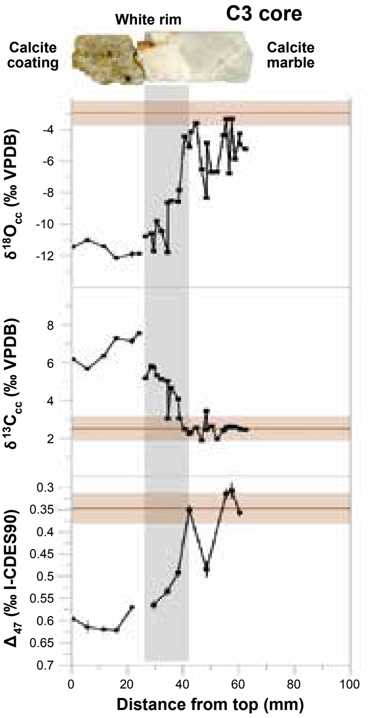
Isotope geochemistry is a powerful tool to study the environment. Its application is not constrained to a single discipline, with various radiogenic and stable isotope analytical approaches being used in studies related to geology, hydrology, climatology, biology, archeology, to name but a few, as well in various industrial applications [1-3].

Over the decades, ATOMKI has carried out, or participated in, various geochemical researches, from age determination of rocks and groundwater, through stable isotopes application to various earth-science topics, up to multi-method approaches combining various stable and radioisotopes to study past climates, water-rock interactions, or trace geofluids and archeological materials.

Curtain stalactite: a specific carbonate formation in caves.

We carry out research on water-rock interactions that includes:

- developing novel approaches to identify isotope alteration in hydrothermal caves using conventional and clumped carbonate stable isotopes,
- study of cave forming processes using sulfur and oxygen stable isotopes in by-products of sulfuric acid dissolution of carbonates,
- Clumped isotope study of tufa deposits and local temperature calibration of carbonate-water oxygen isotope fractionation.



Stable and clumped isotope signatures of altered and unaltered cave carbonates.

We have recently established U-Th dating of carbonates for the reconstruction of palaeoclimate in Europe and South America, and Pleistocene tectonic and landscape evolution in the Balkans. Lead isotope analysis is applied to identify provenance of lead used in production of glaze of high-quality medieval stove tiles. Our noble gas-related research ranges from determining noble gas recharge temperatures of groundwaters up to using noble gas geochemistry of fluid inclusions in minerals to identify deep-sourced mantle and crustal gases.

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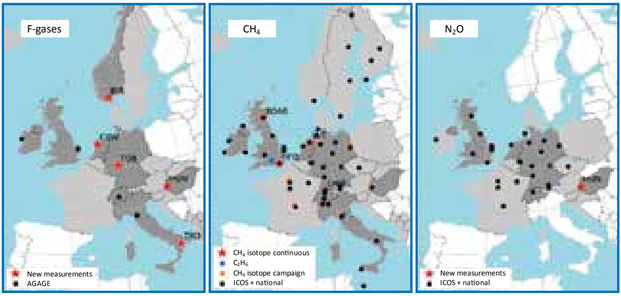
Determination of Regional Greenhouse Gas Emissions

Participation in Horizon Europe PARIS (Process Attribution of Regional Emissions) project; determination of carbon dioxide, methane, nitrous oxide, and F-gases emissions on national level in Europe.

The primary cause of global climate change is the accumulation of greenhouse gases in the atmosphere as a result of human activity and the associated natural feedback. The evolution of the global climate directly depends on anthropogenic emissions and their temporal trends. Therefore, highly accurate emissions data are essential for social and economic preparedness. At present, anthropogenic emissions are calculated by multiplying statistical activity data with emission factors (emission per unit activity) characteristic of the given type of activity. This method cannot give an accurate estimation of the amount of greenhouse gases released into the atmosphere. Partly, it obviously misses the unknown sources, partly the characteristic emission factors do not perfectly fit all actual sources of similar types, and partly the method cannot give information on the natural emissions changing with climate. The actual amount of greenhouse gases released into the atmosphere, which is relevant for climate processes, can be determined by the combination of high-quality atmospheric concentration measurements and detailed atmospheric transport models.

The International Radiocarbon AMS Competence and Training Center of ATOMKI is a participating partner in the Horizon Europe PARIS project (2023-2026), which aims at the determination of the actual greenhouse gas emissions of the European countries applying atmospheric concentration measurements and transport models.



The monitoring networks and the participating countries of the Horizon Europe PARIS project. Dark grey shading indicates the focus countries for which detailed analyses will be prepared.

The International Radiocarbon AMS Competence and Training Center (INTERACT) of ATOMKI is experienced in atmospheric composition measurements and operates the only greenhouse gas monitoring station in Hungary (Hegyhátsál). Its in situ instrumentation and laboratory capacity are able to provide high-quality concentration measurements of carbon dioxide, methane, and nitrous oxide, as well as their isotope composition. In the framework of the Horizon Europe PARIS (Process Attribution of Regional Emissions) project, in cooperation with the Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt, Germany, ATOMKI INTERACT collects flask samples for fluorinated greenhouse gases (F-gases), and house a mobile GC-IRMS facility at Hegyhátsál for the measurements of methane isotopologues. The infrastructure of the groups involved in the PARIS project covers a wide range of trace gas/GHG analyses (several Picarro and Los Gatos CRDS spectrometers), stable-isotope mass spectrometers (Thermo IRMSs for δD, $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $\delta^{34}S$) and radiocarbon accelerator massspectrometer (AMS). The isotope composition measurements help to distinguish between anthropogenic and natural sources, which is a key issue in compiling emission mitigation measures. They also help record the responses of the Earth system to anthropogenic forces, which is important to understand how much we can control the climate change we have triggered.

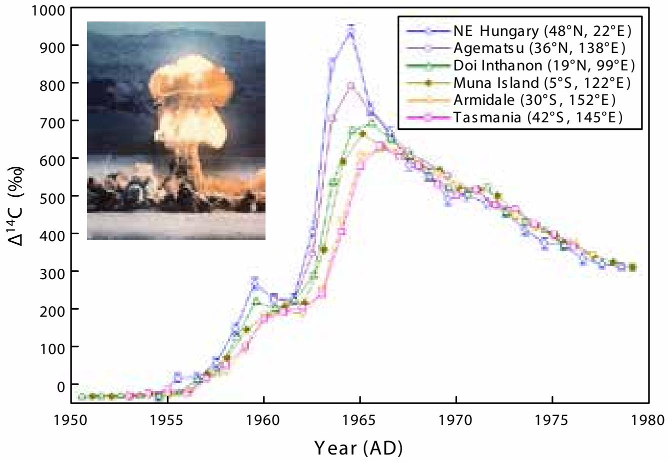
The high-quality atmospheric concentration and isotope composition measurements serve as input data for the atmospheric transport models developed and run by MetOffice, the United Kingdom, and Wageningen University, the Netherlands.

Industrial Applications of ^{14}C

Helping industrial research and development using radiocarbon (^{14}C) as a tracer and identifying anthropogenic pollution sources, examining recent environmental shifts by environmental monitoring.

Since the mid-20th century, human activities have disrupted natural ^{14}C levels. Nuclear weapons testing between 1950 and 1963 nearly doubled atmospheric ^{14}C, creating the bomb peak—a sharp rise in radiocarbon detectable in tree rings, sediments, and even human tissues. This serves as a powerful time marker in environmental and forensic sciences. Nuclear power plants also emit small amounts of ^{14}C as CO_2. Monitoring these emissions is crucial for environmental safety assessments.

The global industrial activities changed irreversibly our world resulting in the Anthropocene. These industrial processes demand wide range of materials from bio to fossil sources. The ^{14}C isotope provides a unique radioanalytical tool for source identification of these plant and petrochemical based materials.



The Bomb Peak Curve – A graph showing the dramatic rise and gradual decline of ^{14}C in the atmosphere since the 1950s. (Graph adapted from Q. Hua, et al., Radiocarbon 55 (2013) 2059, image credit: U.S. Department of Energy.)

ATOMKI's contribution: industrial ^{14}C applications

Quantification of bio and fossil contributions helps the decision makers, industrial partners and supports social expectations as the demand of truly biobased products increases rapidly. Our analytical techniques were applied successfully for solving real industrial problems and were applied in national and international R&D projects.

Using ^{14}C and other isotopes we are able to determine the biocontent ratio in industrial food-chain related samples, such as sweeteners, aromas, vitamins, drug and cosmetics products.

This laboratory is dedicated to quantify the contribution of biocontent in solid, liquid and gas fuel and plastic samples, beside the determination of fossil content in the food chain and industrial samples.

The work of the International Radiocarbon AMS Competence and Training Center (INTERACT) of ATOMKI spans:

Atmospheric Carbon Studies
We analyze C-content of the urban and rural air samples to distinguish fossil fuel emissions from natural sources. Our studies help assess pollution and the efficiency of climate policies [1, 2].

Nuclear Industry and Energy Research
By measuring ^{14}C emissions from nuclear facilities, we evaluate environmental impacts and ensure compliance with safety standards [3, 4].

Food, Medicine, Plastics, and Fuel Verification
Our laboratory applies ^{14}C to detect synthetic carbon content in food, biofuels, medicines, and plastics, supporting sustainable materials and fraud detection in industries [5, 6].

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APPLICATIONS

of nuclear methods in space research,
materials science and quantum technology

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- SPACE CHEMISTRY IN THE LABORATORY
- NUCLEAR CHEMISTRY: ONCOLOGICAL IMPACT FOR NUCLEAR MEDICINE
- FUNCTIONALIZATION OF SOLID SURFACES WITH IONS
- THIN LAYER ACTIVATION FOR INDUSTRIAL TRACING
- PLASMA PHYSICS RESEARCH
- PROTON BEAM WRITING
- RADIATION CHEMISTRY
- MODELLING OF FUSION PLASMA PROPERTIES
- COLD IONIZED MEDIA: THE ROLE OF THE ELEMENTARY COLLISIONS
- OPTICAL PROPERTIES OF MATERIALS
- PEROVSKITE-BASED THIN-LAYER SCINTILLATORS
- ELECTRONICS DEVELOPED FOR SCIENCE

Space Chemistry in the Laboratory

Probing molecular formation in the Cosmos.

As space exploration enters a new age, increased efforts have been made to better understand the extraterrestrial chemistry that shapes our Cosmos; from our closest neighbours in the Solar System to far-flung exoplanets and the depths of the interstellar medium. This flurry of research has also been driven by the fact that the coming decades will see the increased exploitation and human habitation of space, and so novel strategies for the chemical synthesis of materials and pharmaceuticals in space will need to be developed. Such research will help us to address several fundamental questions, such as: How are molecules formed deep in space? Can biomolecules be formed there and, if so, can they be seeded to planets to kick-start the emergence of life there? Could that mean that life may arise elsewhere in the Universe? Can we inhabit other worlds?

To date, over 300 molecules have been identified in interstellar space. Most molecules are believed to form within the cold (10-20 K) nanoscale ices adsorbed on interstellar dust grains. These ices are initially composed of simple molecules (e.g., H_2O, CO, or NH_3); however, energy deposited by incident cosmic rays, stellar winds, ultraviolet photons, and shock waves processes these molecular ices, resulting in the formation of complex organic molecules (COMs) which may enhance the chemical inventory of astronomical environments. Given the potential bio-utility of these COMs, there is a strong motivation to understand interstellar chemistry, leading to their formation using advanced laboratory and computational methods.

At HUN-REN ATOMKI, there exists a unique opportunity to study radiation-induced chemistry in astrophysical ice analogues. The ensemble of our accelerators can be used as a Solar Wind Simulator, since they are able to provide a wide selection of ions having energies analogous to the solar wind and galactic cosmic rays (300 eV – 30 MeV). The Experimental Molecular Physics Group boasts a robust history in the study of ion-molecule collisions, and has recently commissioned five experimental astrochemistry chambers to study ion collision-induced molecular destruction, synthesis, and sputtering in astrophysical ice and gas-phase analogues.

Some examples of our recent research studies include investigating the role of sulphur ions in the surface chemistry of the Galilean moons of Jupiter and the energetic synthesis of biomolecules from simple precursors.

The same facilities may be used to explore radiation-induced physical and chemical damage in materials that are used in spacecraft or being proposed for use in the first structures to be built on the Moon, including those fashioned from the lunar regolith.

During the Europlanet 2024 RI Project (2020-24), our chambers proved to be popular with the worldwide astrochemistry research community, and have been used to carry out over 20 projects. We are working in close collaboration with colleagues from the University of Kent, Queen's University Belfast, and Aarhus University. As a member facility of The Europlanet Society and a leading organisation of the Hungarian Space Chemistry Network, we will strengthen both our national and international collaborations in the experimental field, whilst using computational models to understand radiation-induced chemical and physical transformations. Such work will contribute to ongoing efforts in space exploration and exploitation currently being undertaken by space missions, as well as the planned future human settlement of the Moon and Mars.

An interior photograph of an astrochemical chamber.
The bright yellow light on the left is emitted by an astrophysical ice analogue deposited on a cold substrate when irradiated with an energetic proton beam.

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Nuclear Chemistry: Oncological Impact for Nuclear Medicine

Cyclotron-produced radioactive isotopes form a firm basis of radiodiagnosis and therapy for nuclear oncology. Our group is dedicated to investigating the production of potential radioisotopes for radiolabelling and developing new radiopharmaceuticals for the Hungarian healthcare system, such as those used in well-known PET imaging and human radiology.

PET radioisotopes available at the ATOMKI cyclotron.

Isotope	$T_{1/2}$	Isotope	$T_{1/2}$	Isotope	$T_{1/2}$	Isotope	$T_{1/2}$
^{11}C	20.4 m	^{68}Ga	67 m	^{95}Tc	60 d	^{148}Eu	55.6 d
^{13}N	10 m	^{69}Ge	39 h	^{99}Rh	16 d	^{152}Tb	17.5 h
^{15}O	2 m	^{71}As	65 h	^{100}Rh	20.6 h	^{162}Ho	15 m
^{18}F	110 m	^{72}As	26 h	^{104}Ag	69 m	^{166}Tm	7.7 h
^{22}Na	2.6 y	^{73}Se	40 m	^{105}Ag	41.3 d	^{168}Tm	93.1 d
^{30}P	2.5 m	^{74}Br	25.4 m	^{107}Cd	6.5 h	^{171}Lu	8.22 d
^{34}Cl	32 m	^{75}Br	96.7 m	^{110}In	4.9 h	^{177}Ta	56.6 h
^{43}Sc	3.9 h	^{79}Kr	35 h	^{117}Sb	2.8 h	^{180}Re	2.4 m
^{45}Ti	3 h	^{81}Rb	30.5 m	^{124}I	4.2 d	^{188}Ir	41.5 h
^{48}V	16 d	^{87}Y	13.4 h	^{132}Cs	6.5 d	^{192}Au	5 h
^{52}Mn	5.6 d	^{86}Y	14.7 h	^{135}La	19.4 h	^{194}Au	38 h
^{55}Co	17.3 h	^{84}Y	39.5 m	^{140}Pr	3.4m	^{200}Tl	26.1 h
^{57}Ni	35.6 h	^{89}Zr	78.4 h	^{139}Pr	4.5 h	^{205}Bi	15.3 d
^{64}Cu	12.7 h	^{90}Nb	14.5 h	^{141}Nd	2.5 h	^{206}Bi	6.2 d
^{62}Zn	9.2 h	^{89}Nb	66 m	^{141}Pm	20.9 m	^{207}Bi	31.6 y
^{65}Zn	243 d	^{94}Tc	4.9 h	^{147}Eu	24.6 d	^{234}Np	4.4 d

- Expensive and time-consuming, and can only be produced in an automated system due to its short half-life.
- Requires a small investment to produce.
- Can be produced immediately without any problems.
- The waste must be stored in a radioactive waste repository for a long time until it decomposes.
- Due to its annual half-life, it requires a very long irradiation time, and the waste can only be disposed of in a radioactive cemetery, which is very expensive.

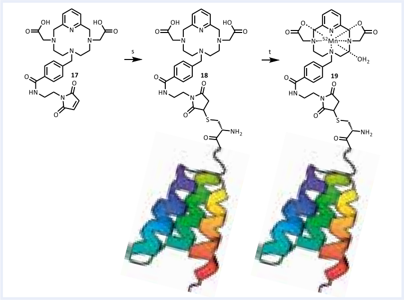
The oncological application of radioisotopes expanded many times in the last decades. For the next research period of the EU Horizon projects oncological research is one of the six priorities of basic research.

Our radiochemical laboratory, equipped with the multiparticle accelerator cyclotron, is the only dedicated infrastructure for radiopharmaceutical research in Hungary. Due to the wide scale of available nuclear reactions, we can cover the periodic table with our radioisotopes and we can produce a long list of isotopes for PET, SPET imaging, the theranostic applications and alpha- and Auger electrons-emitter radioisotope therapy. Some of the possibilities are shown in the table above.

The necessary labelling procedures were also studied and developed in cooperation with the University of Debrecen and many other research partners in Hungary, as well as abroad. For instance, the new families of the chelator agents were applied to create the reaction kinetically stable and thermodynamically suitable complexes to conjugate the bioactive vector molecules, such as affibodies and nanoparticles.

After the successful labelling, we are carrying out preclinical experiments in our cell laboratory using the MiniPET-3 small animal PET camera, which was also developed at ATOMKI. The necessary radioanalytical and radiochemical infrastructure were also renewed in the 2020s.

Cleanroom with the automated hot cells for production of radiopharmaceuticals.



Conjugation and radiolabelling of the 3,9-PC2ABn^{pMMA} BFC ligand to the affibody and its complexation with [^{52}Mn]Mn(II): (s) Affibody $Z_{HER2:2891}$-Cys.

Functionalization of Solid Surfaces with Ions

The Electron Cyclotron Resonance Ion Source (ECRIS) facility of ATOMKI is used (among many other applications) to produce low-energy ion beams for modification and functionalization of solid surfaces, especially surfaces of medical implants and restorations.

Functionalization: changing the surface of a solid body by a carefully selected method for a special goal.

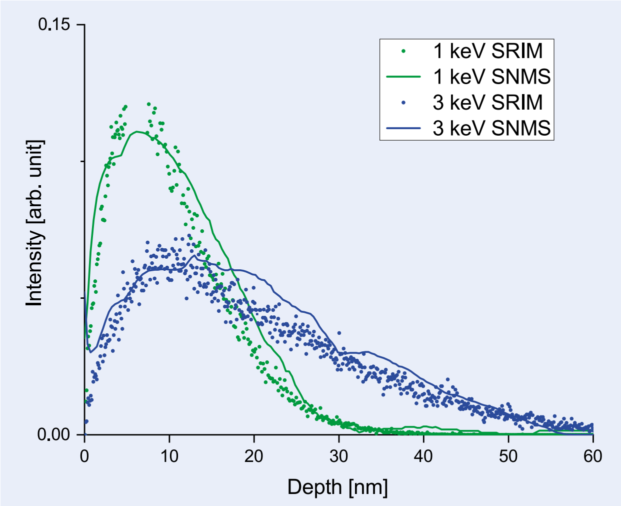
Changing the structure and composition of solid-state surfaces for a well-defined purpose, i.e. functionalization is a key to the widespread, versatile use of these materials. Functionalized surfaces can be found in several areas; from electronics through chemistry to medicine. Modification of surfaces can be carried out by several ways. The afore-mentioned ECRIS can produce low-energy, high intensity ion beams, so it was logical to apply our ion beams for functionalization purposes.

At ion-surface interactions the basic question is always: what sample material should be irradiated by what particles and for what purpose? There are several known material "pairings" (targets-projectiles) such as zirconium–silicon in the case of prostheses; and titanium–gold, titanium–silver and titanium–calcium for implants, which are important for, e.g. dentists. Surface modification usually requires a special equipment which delivers a certain type non-conventional ion beam at appropriate energy and dose, necessary for these irradiations. As another solution, during the last decade we formed our ECRIS into a multipurpose low-energy implanter for surface modifications in a wide range of projectile type, charge, energy and dose. In terms of irradiation dose the ECRIS of ATOMKI is able to provide upto 10^{17} ions/cm^2 within reasonable irradiation time (hours) in case of low and middle-charged beams, generated especially from gases. The implanting depth is usually in the upper 5–200 nm layer of the material surface. We are also able to produce plasma from solid materials using various techniques.

In order to use our instruments and knowledge in physics for medical purposes, our institute has been collaborating with the University of Debrecen and with several foreign partners as well. The joint research projects aimed at the surface modification of dental restorations and implants by low-energy ion beams. In some cases the irradiation of the samples was followed by cell-growing on the modified surface or by bonding strength investigations. The aim is the "functionalization" of the medical sample for a well-developed goal, namely to improve the bonding strength between the metal and living cells, or increase the lifespan or the bacterial properties, etc. Here we report some details on the most promising irradiations, as examples.

Silicon ions into ZrO_2

In dentistry, it is necessary to increase the bonding strength between various bioinert zirconia ceramics and the luting cement in order to extend the lifetime of the restoration. We implanted Si ions just under the surface of the ZrO_2 on nanoscale to improve chemical bonding in between the bonding agent and the zirconium-dioxide. The stronger a material, the higher the load at brake value. The penetration depth was few 10 nanometers into the surface of zirconium ceramics. The Stopping and Range of Ions in Matter (SRIM) simulation and the Secondary Neutral Mass Spectrometry (SNMS) measurement results were in good agreement as shown on the figure here. We found that the load at brake is higher when we apply the combination of 3 kV extraction ECRIS voltage, post-irradiated by oxygen ions and even venting the vacuum chamber with oxygen.



Comparison of the depth distributions of 1 keV (green curve and dots) and 3 keV (blue curve and dots) silicon atoms calculated by SRIM and measured by SNMS.

Thin Layer Activation for Industrial Tracing

In order to measure and follow wear, corrosion or erosion processes in different machine parts, radioactive tracers of known activity and distribution are introduced into the critical points of the sample in question.

In order to measure and follow wear, corrosion or erosion processes in different machine parts, radioactive tracer of known activity and distribution are introduced into the critical points of the sample in question.

The method TLA (Thin Layer Activation) is based on charged particle-induced reactions, where the surface of the machine part to be investigated is irradiated with a charged particle beam of a given type and energy and with the calculated charge in order to produce radioactive tracers in the desired position and depth distribution.

The final activity of the chosen tracer isotope, as well as the activity of the co-produced other radioisotopes is measured, and the decay is followed for correction. Afterward, the sample (machine part) is put into the working environment and by measuring the change in the activity of the tracer isotope(s) the wear, corrosion or erosion rate can be determined as a function of the working and/or environmental conditions. The depth distribution of the activity tracer isotope can be adjusted by the irradiation energy and the collected charge (beam current) respectively. The actual wear measurements are mainly performed by our scientific/industrial partners. Recently we purchased our own tribometer to perform wear measurements of small parts in our laboratory.

The quality of the activation can also be visually checked, based on the positron emitter tracers or co-produced positron emitter isotopes, by using the mini-PET developed in Atomki.

Thin Layer Activation (TLA) technique for wear measurement

B	^{nat}B(d,x)^{7}Be		^{59}Co(d,x)^{58}Co	In	^{nat}In(p,x)^{113}Sn
Be	^{9}Be(^{3}He,αn)^{7}Be	Cu	^{nat}Cu(p,x)^{65}Zn	Sn	^{nat}Sn(p,x)^{124g}Sb
C	^{nat}C(d,x)^{7}Be		^{nat}Cu(d,x)^{65}Zn		^{nat}Sn(α,x)^{121g}Te
	^{nat}C(^{3}He,x)^{7}Be		^{nat}Cu(,x)^{65}Zn		^{nat}Sn(α,x)^{121m}Te
Al	^{22}Al(p,x)^{22}Na		^{nat}Cu(,x)^{67}Ga	Sb	^{nat}Sb(p,x)^{121g}Te
	^{22}Al(d,x)^{22}Na	Zn	^{nat}Zn(p,x)^{65}Zn	Te	^{nat}Te(p,x)^{126}I
	^{27}Al(d,x)^{24}Na		^{nat}Zn(d,x)^{65}Zn	Yb	^{nat}Yb(p,x)^{173}Lu
	^{27}Al(^{3}He,x)^{22}Na	Y	^{89}Y(p,2n)^{88}Zr		^{nat}Yb(d,x)^{175}Yb
	^{27}Al(,x)^{22}Na	Zr	^{nat}Zr(d,x)^{92m}Nb		^{nat}Yb(d,x)^{173}Lu
Ti	^{nat}Ti(p,x)^{48}V		^{nat}Zr(p,x)^{92m}Nb	Ta	^{181}Ta(,2n)^{183}Re
	^{nat}Ti(d,x)^{48}V		^{nat}Zr(d,x)^{91m}Nb		^{181}Ta(d,p)^{182}Ta
	^{nat}Ti(d,x)^{46}Sc	Nb	^{93}Nb(p,x)^{92m}Nb	W	^{nat}W(p,x)^{183}Re
	^{nat}Ti(^{3}He,x)^{48}V		^{93}Nb(d,x)^{92m}Nb		^{nat}W(p,x)^{184}Re
	^{nat}Ti(,x)^{51}Cr		^{93}Nb(d,x)^{91m}Nb		^{nat}W(d,x)^{183}Re
V	^{nat}V(p,x)^{51}Cr	Mo	^{nat}Mo(p,x)^{96}Tc		^{nat}W(d,x)^{184}Re
	^{nat}V(d,x)^{51}Cr		^{nat}Mo(p,x)^{88}Zr	Re	^{nat}Re(p,x)^{185}Os
Cr	^{nat}Cr(p,x)^{52}Mn		^{nat}Mo(d,x)^{96}Tc		^{nat}Re(d,x)^{185}Os
	^{nat}Cr(d,x)^{51}Cr		^{nat}Mo(d,x)^{88}Zr	Os	^{nat}Os(d,x)^{192g}Ir
	^{nat}Cr(d,x)^{54}Mn	Rh	^{103}Rh(p,n)^{103}Pd	Ir	^{nat}Ir(d,x)^{191}Pt
Mn	^{55}Mn(p,x)^{54}Mn		^{103}Rh(d,n)^{102g}Rh		^{nat}Ir(d,x)^{192g}Ir
Fe	^{nat}Fe(d,x)^{57}Co		^{103}Rh(d,n)^{103}Pd	Pt	^{nat}Pt(p,x)^{195g}Au
	^{nat}Fe(p,x)^{56}Co	Pd	^{nat}Pd(p,x)^{105}Ag		^{nat}Pt(p,x)^{196}Au
	^{nat}Fe(,x)^{58}Co		^{nat}Pd(p,x)^{110m}Ag		^{nat}Pt(d,x)^{195g}Au
Ni	^{nat}Ni(p,x)^{57}Ni		^{nat}Pd(d,x)^{110m}Ag		^{nat}Pt(d,x)^{196}Au
	^{nat}Ni(p,x)^{57}Co	Ag	^{nat}Ag(p,x)^{105g}Ag	Au	^{197}Au(p,pn)^{196g}Au
	^{nat}Ni(d,x)^{56}Co		^{nat}Ag(d,x)^{110m}Ag	Tl	^{nat}Tl(p,x)^{202}Tl
Co	^{59}Co(p,x)^{57}Co		^{nat}Ag(d,x)^{105g}Ag	Pb	^{nat}Pb(p,x)^{206}Bi
	^{59}Co(p,x)^{58}Co	Cd	^{nat}Cd(p,x)^{114m}In		^{nat}Pb(p,x)^{205}Bi
	^{59}Co(d,x)^{60}Co		^{nat}Cd(α,x)^{113}Sn		

An online database was established by the IAEA (International Atomic Energy Agency) with the data of the known reactions.

The online database (*https://www-nds.iaea.org/tla/*) as well as the downloadable Excel workbook help the user/customer to calculate the parameters of his/her wear measurement. One can calculate with 86 charged particle induced nuclear reactions on 35 elements with protons, deuterons, ^{3}He and alphas as bombarding particles in a wide energy range of small and medium energy particle accelerators. The calculation can be done online or by using a downloadable Excel workbook. In such a way our scientific partners can check the feasibility of the desired wear measurement task in advance.

The program in many cases also calculates the co-produced, unavoidable contaminating radioisotopes, and gives the dept distribution and the parameters of the tracer isotopes. All of them are at the end of bombardment and also after an adjustable cooling time.

The most frequently requested radioisotopes are ^{57}Co and ^{56}Co from the iron content of the machine part by deuteron and proton irradiation, respectively. In the case of non-metallic parts, plastic, DLC-coating, etc. the ^{3}He irradiation of carbon content produces ^{7}Be in the sample, which is a proper tracer both from the point of view of gamma-radiation and from the half-life.

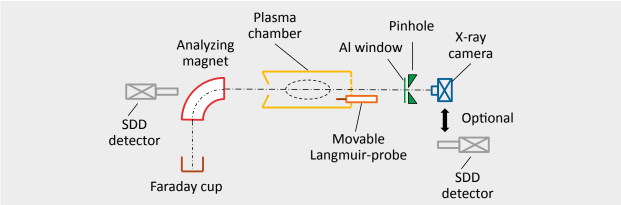
Plasma Physics Research

The goal of laboratory plasma physics studies at one of the ATOMKI accelerators is to optimize plasma parameters and to improve short-term and long-term plasma/beam stability including astrophysics relevancy.

Plasma exists in nature where the temperature is adequately high, such as in the Sun, stars and in the ionosphere. Beside the solid, liquid and gaseous states, plasma is called as the fourth state of matter. In plasma, some of the orbital electrons of atoms are stripped from their nuclei and are free to act as individual particles in the surrounding electromagnetic field. Interactions that take place between plasma particles (ions, electrons, neutrals) are much more diverse than for gaseous state.

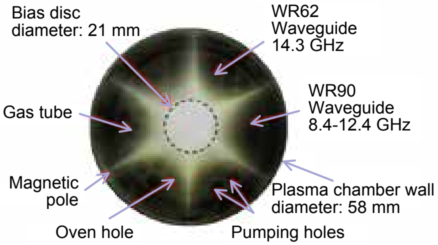
Laboratory plasmas can be created in many ways, most commonly in electrical discharge. In order to understand better the plasmas themselves and plasma behavior, plasma physics research nowadays concentrates to several directions. The main interests in this field include studying plasma confinement and stability, plasma heating and fusion, plasma interactions with electromagnetic fields, and plasma applications in various industries such as energy, materials processing, and space exploration.

Plasma physics research carried out in ATOMKI mainly concentrates on the investigation of laboratory plasmas, especially plasmas from Electron Cyclotron Resonance (ECR) Ion Sources (ECRIS). Such kind of ion sources are usually used to provide variously charged heavy ions to high-energy accelerators (e.g. cyclotrons, synchrotrons). We are developing and applying plasma diagnostics methods in order to improve the beam parameters (brightness, emittance, temporal stability) extracted from the ECR plasma. Those methods are able to refer the most important plasma parameters (e.g. plasma density, density distribution, plasma temperature, plasma potential, plasma stability) and are schematically illustrated by the following figure.



Schematic illustration of plasma diagnostic methods surrounding the plasma chamber.

Plasma discharges can be investigated experimentally by two basically different methods: global and local plasma diagnostics. The first one is based on the fact that the plasmas emit radiation in the infrared (IR), visible light (VL), ultraviolet (UV), and X-ray (XR) regions of the electromagnetic spectrum. The measurement and the analysis of photos and spectra taken in any of these regions are usually feasible tasks and give valuable insight into the plasma structure and the properties of the discharges, as well as the processes that create the radiation. The non-destructive nature of this method is certainly an advantage. When small-size electrically biased electrode (Langmuir-probe) placed close to or inside the plasma provides local information on the plasma parameters by the evaluation of the voltage-current characteristics of the probe. It is a destructive method, but gives spatially well separated, local plasma parameters. Plasma parameters obtained by the different diagnostics methods as function of the setting parameters of the ECR ion source are really helpful to further optimize the source conditions and to reach as high intense and as highly charged heavy ions as possible. Those efforts significantly advance the nuclear physics experiments carried out at the beamline of high energy accelerators. Our plasma research has importance in several European project. One of them is PANDORA: Plasmas for Astrophysics, Nuclear Decay Observation and Radiation for Archaeometry. PANDORA aims to measure, for the first time, nuclear β-decay rates in stellar-like conditions, in ECR type, magnetized plasmas. Plasmas will be generated from radioactive isotopes and the decay rate will be investigated. In order to correctly evaluate the decay events and rates, online monitoring of plasma density, temperature and CSD (Charge State Distribution) is required. In strong collaboration with the project leader (INFN-LNS, Catania, Italy) our group is working on a multi-diagnostics setup, which can provide all the local and global plasma parameters to reach the complete interpretation of the PANDORA results.

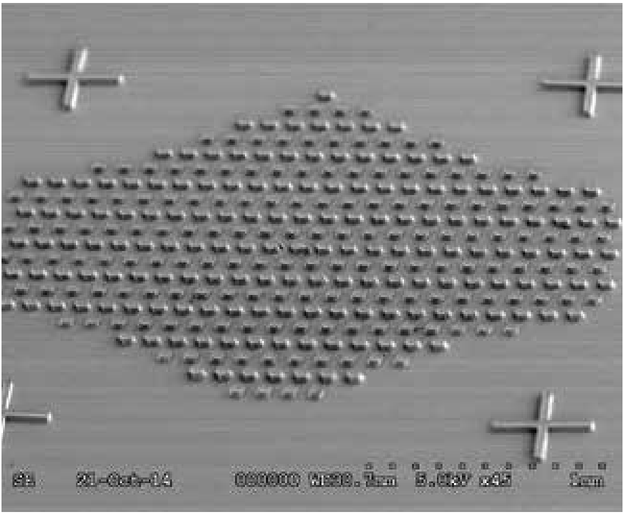


Plasma photo taken of ECR plasma in visible light range.

Proton Beam Writing

Focused MeV energy ion beam is scanned over a suitable resist material, and subsequently chemically developed.

Proton Beam Writing (PBW) is a three-dimensional direct-writing lithography process utilizing a focused beam of MeV protons to pattern resist materials at micro or nanoscale dimensions. While the process is similar to electron-based direct writing, it presents unique advantages. Due to their greater mass, protons can penetrate materials deeper while maintaining a straight trajectory. This capability empowers PBW to create three-dimensional structures with high aspect ratios, featuring vertical, smooth sidewalls and minimal line-edge roughness. Moreover, PBW demonstrates minimal proximity effects due to the low-energy secondary electrons produced in proton/electron interactions. Another benefit arises from protons' ability to displace atoms as they traverse materials, leading to enhanced localized damage, particularly at the end of their range. As a result, PBW enables the creation of resistive patterns deep within silicon, facilitating selective patterning of regions with distinct optical properties and the removal of undamaged areas through electrochemical etching.



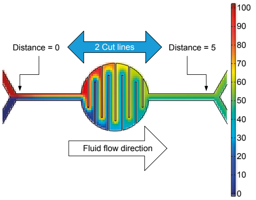
Scanning electron microscopy image of doubly tilted micropillars, fabricated in PDMS by polymerization with focused proton beam on the top of a cross-linked PDMS layer.

We developed a microfluidic cell capture device using PBW for multi-angle lithographic irradiation and UV lithography to easily create large-area structures. The device features a doubly tilted micropillar array for enhanced cell manipulation. Tilting the pillars increased their surface area, improving fluid interaction when bioaffinity coatings were applied and optimizing fluid dynamics during cell culture injection. The microstructures effectively distributed body fluids like blood and spinal fluid between reservoirs, enabling advanced cell capture.

Another illustrative example of PBW application involved enhancing the efficiency of a microfluidic passive mixer through microstructure functionalization. We undertook the complete design, simulation, and realization of various microfluidic passive mixer devices. To enhance mixing efficiency within these devices, we strategically incorporated microstructures into the mixing unit area. In our design process, we utilized COMSOL simulations to optimize the shapes and layouts of these microstructures.

It is widely recognized that a micro-wall array is a promising tool to improve mixing in microfluidic passive mixer devices. We conducted experiments where we systematically varied both the length and areal density of the walls within the micro-wall array to determine their impact on mixing performance. Subsequently, we manufactured these devices using PBW and UV lithography techniques.

Following fabrication, we conducted mixing tests to assess the efficiency of these passive micromixers. The results revealed that an excellent level of mixing efficiency could be achieved by employing densely distributed and longer micro-walls within the devices.



COMSOL simulation of mixing of two fluids.

Electron microscopic image of a real mixing unit area.

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Radiation Chemistry

Radiation chemistry deals with the study of chemical processes occurring in matter due to ionising radiation and with the development of methods for quantifying the radiation resistance of various materials.

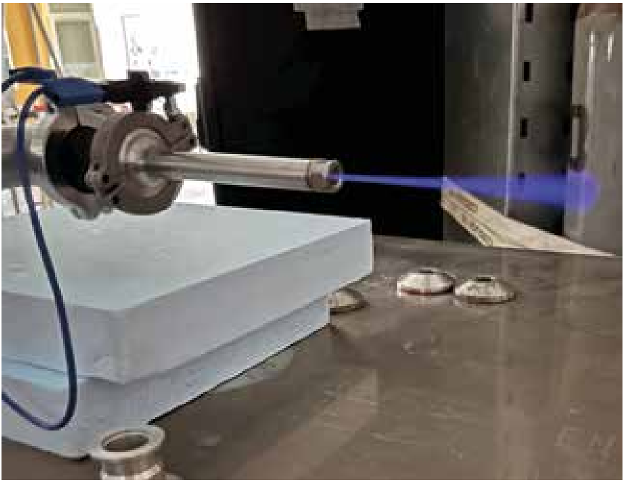
Radiation is part of our Earth and has always been; it may affect life and might even have played a crucial role in the emergence of life. A fundamental understanding of the effects of radiation has often been at the heart of important scientific and technological breakthroughs.

A major contemporary challenge is the quantitative understanding of physical and chemical processes in complex systems. Such processes may be essential, for instance, in adapting and applying catalytic processes to industrial chemistry settings, in developing new forms of radiation therapy, energy transformation and storage, etc. Through radiation chemistry studies, the radiation tolerance of materials (most notably space-relevant materials) can also be determined. Moreover, the radiation treatment of wastewaters may allow for the removal of otherwise non-degradable drug molecules.

As a result of its interaction with ionising radiation (at ATOMKI, beams of protons and other ion species are most commonly used), the molecules in target materials may be ionised or excited, which may lead to bond scissions and the formation of new bonds resulting in significant changes to the chemical properties of the target material. The determination of such ion irradiation-induced chemical changes is performed using UV-visible, infrared, and luminescence spectroscopic techniques at ATOMKI. As a result of the scission of bonds, reactive radicals such as the hydroxyl radical (•OH) may be formed. It is also possible for two radicals (e.g. carbon atoms) to recombine, emitting photons at characteristic energies in the process. This effect is almost equivalent to chemiluminescence, which can be studied by spectrometric and time resolved methods.

The use of Attenuated Total Reflectance Fourier Transform InfraRed spectroscopy (ATR-FTIR) analysis techniques are especially effective to measure chemical changes in irradiated polymers. To detect reactive intermediates (e.g. radicals, solvated electrons), scavenging techniques can be applied.

The ion accelerators available at ATOMKI can provide a wide variety of projectiles; including light (e.g. proton, He^{+} ions) and heavier (e.g. C^{+}, O^{+}, S^{+}) ions over a wide energy range covering the solar wind and cosmic ray energies, thereby allowing us to perform space-related research. Most of the irradiations are performed using a special experimental arrangement, in which the ion beam is extracted into air. The radiation resistance of molecules relevant to biology will form a special focus for our future research work.



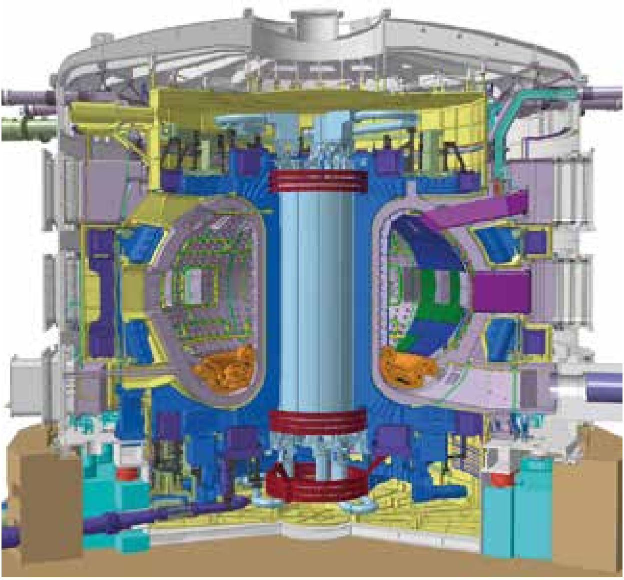
The external beam at Tandetron accelerator. Air molecules are excited by the extracted ions and glow. The same happens in the northern lights (aurora borealis).

Luminescence from acetone induced by proton beam.

Modelling of Fusion Plasma Properties

Comprehensive review and computation of cross-sections essential for the modelling of fusion plasmas.

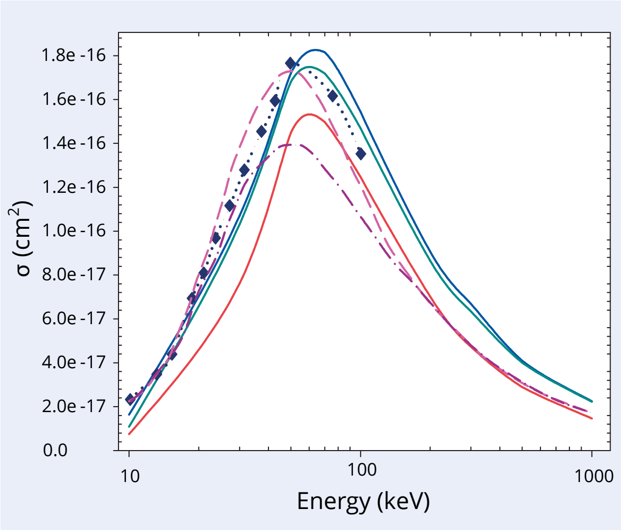
The currently used energy production methods will not be able to satisfy the energy needs of humanity in the long run. In the absence of a rapid increase in energy storage efficiency, it is becoming increasingly urgent to develop an environmentally friendly and regulated solution for a new energy source. One of the most auspicious solutions for the future could be the implementation of fusion power plants. Fusion is capable of generating vast amounts of energy using very little 'fuel'.



Schematic diagram of the fusion reactor.

Although tremendous efforts have been made over the past decades to achieve a positive-balance and practical energy-producing reactor, it still does not exist today. The reason for this lies in the complex nature of the physical challenges and the unusual range of material properties. At the microscopic level, the interactions are based on the collisions of different particles. In the past, the collision process was modelled using a wide range of theoretical techniques.

However, it is recognized that even the available basic cross-section data are not accurately known. As an illustration, we show the ionization cross-sections in collision between proton and hydrogen atoms.



Ionization cross-sections in H^+ + H (1s) collision
as a function of impact energy.

Atomic physics processes rarely play a role in the high-temperature central regions of fusion plasmas, but are definitely an issue at the outmost layer of the scrape-off layer, and even more at the region of plasma-wall interaction. Another field where atomic physics is essential in fusion plasmas is the interaction of high-energy atomic beams with plasma particles. Both plasma-wall and beam-plasma interactions include high-energy collisions. Among many others we are working on to bring the relevant atomic cross-section data to the state-of-the-art. One of such ventures is the Coordinated Research Project F43026 on Atomic Data for Injected Impurities in Fusion Plasmas organized by the International Atomic Energy Agency (IAEA). The main objective of the work is the accurate calculation of the fusion research interest cross-sections and to perform validation in comparison with our experimental data. We are open for any collaboration in this field and appreciate every inquiry. We plan to give recommended cross-section data for the investigated systems and generate a database as a result of our calculation.

Cold Ionized Media: The Role of the Elementary Collisions

The collision of photons, electrons or ions with atomic and molecular species are commonly occurring phenomena; the detailed knowledge of all related elementary collisional processes is crucial to understand and model these environments in nature.

The essence of the recent explosive developments in quantum physics, the so called "second quantum revolution", is that we are not only observers of the phenomena of the quantum world, but we are actively intervening in their dynamics. By imposing on the constituents – atoms, molecules, ions, electrons and photons – specific motions obeying the laws of quantum mechanics, we will be able to control and manipulate matter at the quantum level through lasers, external electric and magnetic fields, or through collisions with particles.

The major questions we address in our group is how an atomic or molecular system responds to an external influence induced by ions, electrons, or photons. Besides understanding the experimental observations, the use of specific quantum states of the initial/incoming and final/outgoing channels helps the full quantum control of these scattering processes. The quantum-controlled reactions will have positive impact on our environment, since they reduce considerably the unwanted by-products of the reactions, which are one of the main challenges for standard chemical processes.

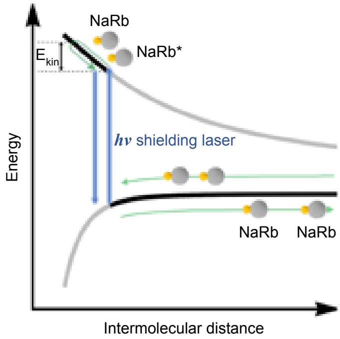
Our theoretical interests are connected to high precision astrophysical observations, new-generation storage-ring measurements and ultracold quantum gas related experiments where the developments in the last decades made possible the investigation and control of collisions at quantum level. The implementation and full control of these systems requires the combined application of higher-level atomic and molecular physics, quantum mechanics and optics, quantum chemistry, and quantum scattering methods in which our group has acquired considerable expertise in the last decades.

The basic knowledge we are able to provide is also of fundamental importance for the formation and destruction of atomic and molecular species in the interstellar medium, for the kinetic modelling of cold, ionized technological plasmas, for the elementary processes of planetary atmospheres, for understanding the role of slow secondary electrons/ions in radiation therapy, and for the modeling of the relative abundance of the chemical elements in the early Universe.

In the last decades, the state-to-state multichannel scattering method – the Multichannel Quantum Defect Theory – developed in collaboration with French research groups has been successfully applied in a series of studies involving the low-energy electron driven reactivity of molecular systems. They provided fully differential collisional data indispensable for the understanding and modelling the multi-electron excitation, ionization, recombination and fragmentation of diatomic and small polyatomic molecules.

One example for manipulating molecular collision on quantum level is related to the control of reactive processes. Laser light can be used to engineer the long-range interaction of the colliding partners to prevent unwanted inelastic processes.

In collaboration with French researchers, we have shown that the entrance channel of two colliding ultracold atoms or molecules can be coupled to a repulsive collisional channel by laser light in such a way that the overall interaction becomes repulsive: this prevents them to come close together and to undergo inelastic processes. The role of spontaneous emission and photoinduced inelastic scattering is also investigated as limitations of the achieved optical shielding efficiency.



Optical shielding scheme for the collision of two ultracold NaRb molecules. The grey curves represent the potential energy surfaces of the ground attractive (lower) and repulsive excited (upper) states of the molecular complex. The use of a resonant laser light (blue) prevents the formation of a bound molecular complex forcing the molecules to move on the pathway presented in black.

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Optical Properties of Materials

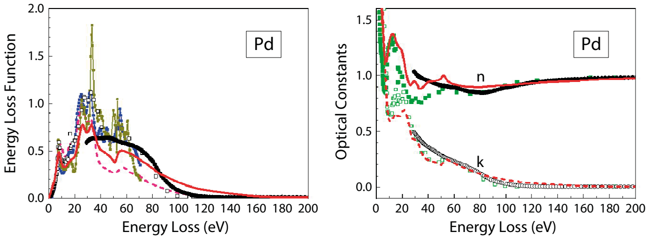
Comprehensive review and accurate determination of optical properties of functional and nanomaterials by a high precision analysis of Reflection Electron Energy Loss Spectroscopy (REELS) spectra.

The optical constants and dielectric function are defined by the response of electrons of a solid to an external electric field. Such information has fundamental importance in both theoretical studies, applied physics and many applications. If we know accurately the optical constants of the given material, practically we can derive all properties and parameters of the material.

Based on the experience accumulated over the years, the electron energy loss spectroscopy that we use for the determination of optical constants has many advantages over traditional methods. We have verified the reliability and accuracy of our method. We have done this because there is ongoing interest and effort in determining the optical constants of solids very accurately.

The revival of the current research is partially justified by the fact that these data are still barely known for many substances, or that the data available in the current database are inaccurate.

As an illustration of the current chaotic situation, we show the energy loss function and optical constants of Pd.

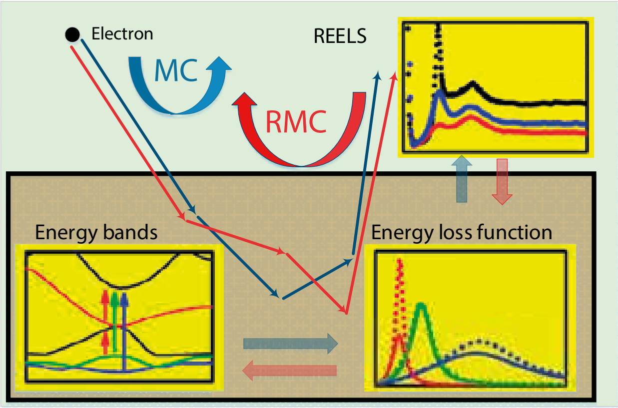


Energy loss function and optical constants of Pd.

In recent years, we have developed a high-precision method based on energy loss spectroscopic measurements of electrons backscattered from the examined sample.

We named the method as Reverse Monte Carlo method (see the Figure below). Our method combines accurate simulation of backscattered electron loss spectra with a global optimization procedure. We describe our initial test loss function with a multi-parameter function.

At the end of the time-consuming iterative calculation procedure, the calculated and measured spectra must match within the measurement error. Then the last loss function of the iteration will be the high-precision loss function characteristic of the given material, from which the optical characteristics of the material can be derived. We have widely used and will use this method to simple bulk and thin film samples in order to accurately determine the optical properties of the given sample.



Schematic view of the Reverse Monte Carlo simulation model.

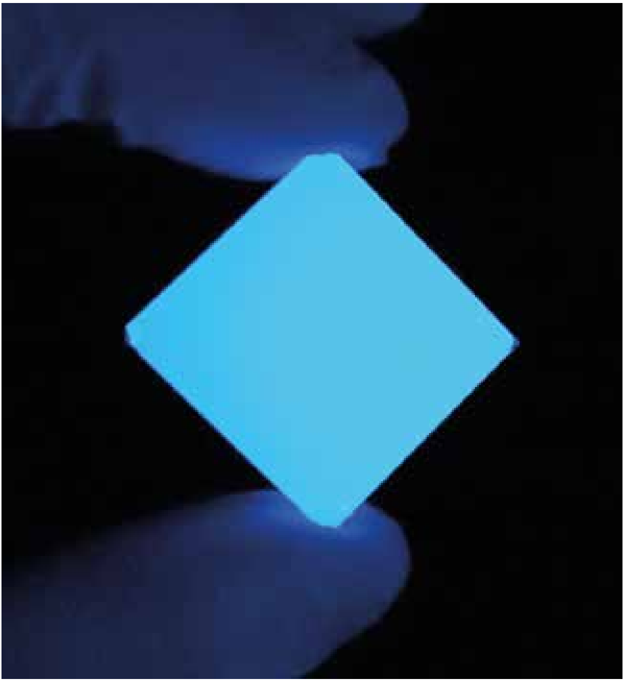
Our scientific goal is to perform a series of measurements and calculations for elements relevant in microelectronics or for fusion research.

Our fundamental scientific researches about the physical properties of important industrial materials, including semiconductors, fusion related metals, rare earth elements which are strongly related to present and future applications, may have a very strong interest for the scientific communities.

We are open for any collaboration in this field and appreciate every inquiry. As a final contribution, we plan to publish our calculated results in either a public database or several books or both.

Perovskite-Based Thin-Layer Scintillators

We have developed and demonstrated inorganic thin-film scintillators with optical pulse characteristics and light yield competitive with conventional single-crystal scintillators, while also providing improved structural and functional stability under extreme environmental conditions.

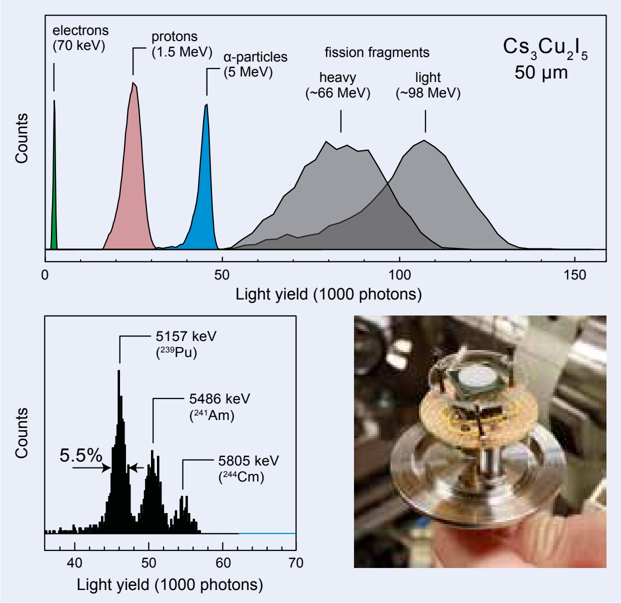


Scintillators have long been powerful tools in radiation detection, however, cannot offer a practical alternative to solid-state detectors in charged-particle spectroscopy. The two main reasons are related to the common experience of their poor energy resolution, and technological obstacles of producing thin films adopted to the short stopping range of MeV-scaled particles, which obey criteria of long-term stability and high luminescence yield. Conventional scintillator materials appear to have various properties that raise functional and stability concerns that can be overcome by developing polycrystalline thin-layers, however, only a limited number of materials is capable of the desired spectroscopic performance.

To find a competitive solution our work was inspired by the sudden rise of synthetic perovskites due to the recognition of their outstanding optoelectronic behaviour. Perovskite research has mainly focussed on photovoltaic and light-source applications, while marginally on the development of X-ray detectors. In contrast, particle-induced scintillation have not been explored so far. Exploiting the availability of a rich compositional landscape of perovskites, we have selected the group of copper-halide compositions, which have been proven advantageous in many physical and chemical parameters to the majority of scintillator materials.

Thin layers were successfully built with a polycrystalline morphology in the thickness range of 1-100 µm. The brightest composition of the group was $Cs_3Cu_2I_5$ with a scintillation yield of 20000 photons/MeV for protons, and the energy resolution for α-particles was 5.5%.

A systematic measurement with heavy-ion beams has also been performed to show the sensitivity and linearity of particle detection in the range of 0.01-1 MeV/nucleon. Furthermore, we have tested the tolerance factors for radiation damage and thermal shock to demonstrate the potentials and performance limitations in space applications and under harsh environmental conditions.



Charged-particle radiations spectroscopically analysed with the $Cs_3Cu_2I_5$ perovskite layer.

Electronics Developed for Science

Electronics – especially nuclear electronics – has always been an outstanding field of development in ATOMKI. Here we list the most important projects and results achieved in the past decades.

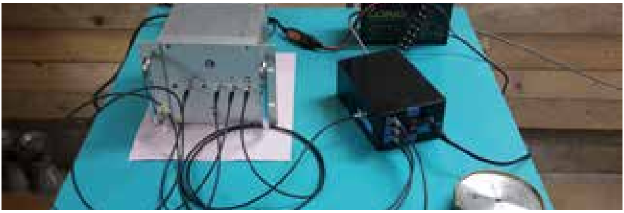
The European Spallation Source (ESS) has been built in Lund (Sweden) in cooperation of 13 member countries including Hungary. This facility is planned to be the brightest neutron source of the world for research purposes. ATOMKI, as an in-kind partner of ESS, has developed and delivered the radiofrequency local protection system for the linear accelerator.

Signal Conditioning Box developed for ESS.

Positron Emission Tomographs (PETs) for small animals were created and further developed in three consecutive projects. The last project resulted in the so-called MiniPET-3, the detectors of which are built of SiPMs (Silicon-based PhotoMultipliers). The detectors, electronics and mechanical parts are ATOMKI contributions, the software was added by the Institute of Nuclear Medicine (University of Debrecen).

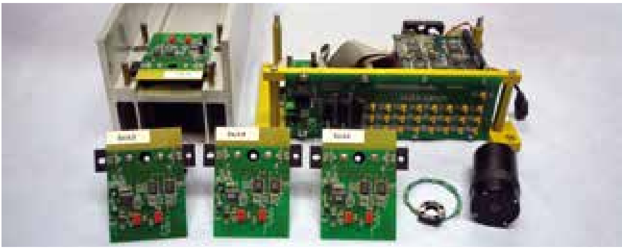
The MiniPET-3 scanner is continuously used in clinics.

A very sensitive (sensitivity: 1 V/Pa, noise: 1 mPa peak-to-peak) infrasound detector has been developed in ATOMKI and can be utilized in various fields. Gravitational wave observatories, like LIGO and VIRGO need to detect the infrasound background very precisely and effectively. Our detectors have already been installed in VIRGO and applied in Einstein Telescope project.



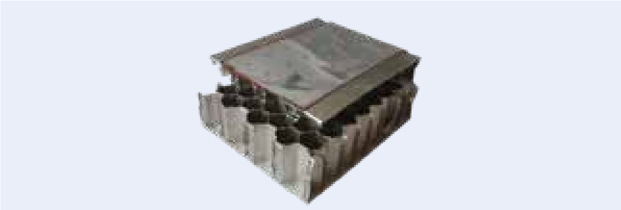
Detection of infrasound background in a mine.

The CERN CMS (Compact Muon Solenoid) detector has been equipped with the so called Muon Barrel Alignment, a very precise (precision: 50 µm) positioning system developed in ATOMKI. This system is still in use, maintained and operated by researchers of ATOMKI.



Electronic units of the CERN CMS Muon Barrel Alignment system.

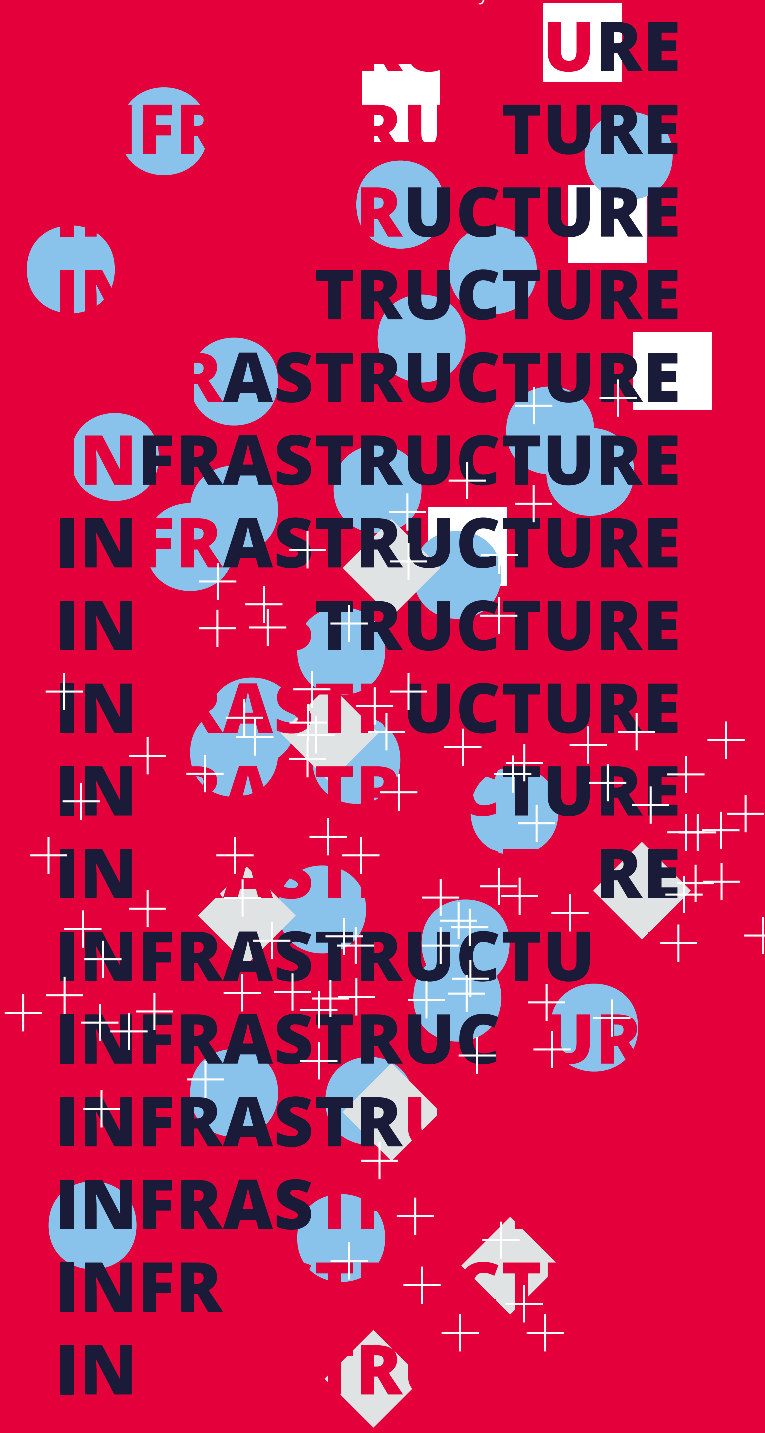
Electronics and other parts of a system can easily be damaged in a harsh environment: because of the radiation near radioactive objects or the cosmic rays during space missions. We have been involved in several radiation hardness tests, among others in ESA SMART-1 and PuliSpace projects due to the various radiation types available in ATOMKI.



The surface of this multilayer plate developed for SMART-1 was cracked during the radiation hardness tests in ATOMKI.

INFRASTRUCTURE

Serving local and international partners
from science and industry



INFRASTRUCTURE

Serving local and international partners
from science and industry

- **TANDETRON LABORATORY**
- **ION BEAM ANALYSIS FACILITY**
- **SPACE CHEMISTRY LABORATORIES**
- **CYCLOTRON: THE MULTI-PARTICLE, MULTI-PURPOSE ACCELERATOR**
- **FAST NEUTRONS FOR BASIC SCIENCE AND APPLICATIONS**
- **EXTERNAL BEAM LINE FOR INDUSTRIAL IRRADIATIONS**
- **THE ELECTRON CYCLOTRON RESONANCE ION SOURCE (ECRIS)**
- **STABLE AND CLUMPED ISOTOPE MASS SPECTROMETRY**
- **RADIOCARBON COMPETENCE CENTER (INTERACT)**
- **LABORATORY FOR HERITAGE SCIENCE**
- **COMPLEX SAMPLE ANALYSIS IN THE FIELD OF MATERIALS SCIENCE**
- **NEPTUNE PLUS MC-ICP-MS**
- **NOBLE GAS MASS SPECTROMETRY**

Tandetron Laboratory

The Tandetron Laboratory is based on a 2 MV Medium-Current Plus Tandetron Accelerator System manufactured by High Voltage Engineering Europa B.V. The project was funded by the Infrastructural Grants administered by the Hungarian Academy of Sciences, as well as by the GINOP-2.3.3-15-2016-00005 grant (Economic Development and Innovation Operational Program) by the European Regional Development Fund (ERDF).

The laboratory is supplied with the required quality of cooling water (temperature, pressure and conductivity controlled) and air conditioning (temperature and humidity controlled). There is an easy access to the laboratory for equipment, staff and visitors. In the auxiliary rooms a chemistry laboratory is also available.

The accelerator is equipped with three ion sources providing stable, high intensity and high brightness ion beams of Hydrogen, Helium and heavy ions (e.g. Lithium, Carbon, Oxygen, Sulphur, Silicon, Copper, Silver, Tin, etc.). On the high-energy end a 90-degree analyzing magnet has been deployed that improves energy stability. The switcher magnet has 9 exit ports, where beamlines are built dedicated to various experiments. Presently there are still 2 free ports available for new experimental setups.

The external beam setup is equipped with a fast-closing gate valve in order to protect the accelerator system. This beamline also serves as a multi-purpose platform for various experiments. In this case the X-ray detector cluster is removed, and only a single KF-40 flange serves for the connection of a dedicated vacuum chamber.

The needs of the new nanoprobe were considered for the site design (layout, orientation). The ‘floating’ concrete base provides a low-vibration environment. The microprobe is based on a quadrupole magnetic lens system in the Oxford-triplet configuration. The nanoprobe utilizes new generation quadrupole magnetic lenses in the Oxford-spaced-triplet configuration. Both have a high precision SmarAct sample manipulation stage (XYZ translations and one axis rotation). Ion Beam Analysis (IBA) can be performed with X-ray and particle detectors (PIXE Proton Induced X-ray Emission, RBS Rutherford Backscattering Spectrometry).

The Tandetron Laboratory. The accelerator is on the right, the beamlines are on the left.

The main parameters are the following:

- Proton energy: 200 keV - 4 MeV, current: up to 200 eμA, brightness: 8-16 Amp(rad)$^{-2}$m^{-2}eV^{-1}
- Helium energy: 200 keV - 6 MeV, current: up to 40 eμA
- Other ions: e.g. Li, C, O, S, Si, Cu, Ag, Sn etc., energy: 200 keV~20 MeV (depending on charge state), current: up to 10-50 eμA (depending on ion species)
- Terminal voltage stability: ± 30 V / 4 hrs (slits stabilization)
- Terminal voltage ripple: 25 V_{RMS}

Beamlines:

- External beam (Ion Beam Analysis – IBA, radiation chemistry)
- Nuclear astrophysics
- Scanning ion microprobe (IBA, proton beam writing)
- Scanning ion nanoprobe (under development)
- Analytical endstation
- Europlanet
- Nuclear physics

Other accessories:

- XYZ stage for heavy items
- Optical microscopes
- UV-VIS-Infra spectrometers
- Glovebox etc.

The switcher magnet with the beamlines.

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Ion Beam Analysis Facility

The Ion Beam Analysis facility at ATOMKI consists of milli-, micro- and nanoprobe endstations both in-vacuum and external beams.

Accelerator based ion beam analytical (IBA) techniques are widely used for the structural and compositional characterization of materials. IBA is based on the interaction of an energetic ion beam with the electrons and nuclei of the atoms in the material under investigation. Depending on the type of interaction X-rays, gamma rays, primary scattered or secondary particles are emitted with energies characteristic to the emitting atom or nucleus. The advantages of the IBA methods are that they are fast, sensitive, multi-elemental, produce high-accuracy quantitative results, they require no or very minimal sample preparation, and very small quantities can be measured in a quasi non-destructive and non-invasive way. Further advantage of IBA is analysis can be done in-air in the case of vacuum-sensitive or large samples. With the simultaneous application of complementary IBA techniques a complex analysis of a sample can be achieved in a single measurement in a very short time (typically few minutes). Ion beam analysis has a wide range of applications: environmental and atmospheric research, materials science, thin layer analysis, biology, medicine, geology, heritage science and many others.

IBA (PIXE-PIGE) analysis of an enameled plaque of the Reliquary of Pétermonostora (Katona József Museum of Kecskemét) at the external microbeam.

At the Tandetron accelerator, several state-of-the-art measurement setups are available for the characterization of different samples in macroscopic or microscopic scale.

The nanoprobe endstation at ATOMKI.

The main parameters are the following.

External millibeam:

- Ion Beam Analysis for large or sensitive objects
- X-ray detector array containing 4 SDD detectors
- Optional helium flow to reduceArgon X-ray background
- Computer controlled sample manipulator
- Radiation chemistry

In-vacuum nanoprobe:

- Oxford Spaced Triplet new generation quadrupolelens configuration
- “Dog-leg” magnetic beam scanning
- High precision large range sample positioning by SmarAct stage

Millibeam in-vacuum:

- PIXE
- RBS
- ERDA
- Channeling
- Heatable sample holder (up to 500 °C)

Microprobe (in-vacuum and external):

- Oxford Triplet quadrupole lens configuration
- Ultra-thin windowed SDD X-ray detector for light elements PIXE
- Beryllium windowed Si(Li) X-ray detector for trace elements PIXE with optional selective filters
- Particle detectors for RBS
- Gamma detector for PIGE
- PBW - Proton Beam Writing
- High precision large range sample positioning by SmarAct stage

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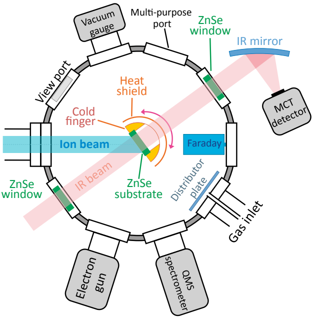
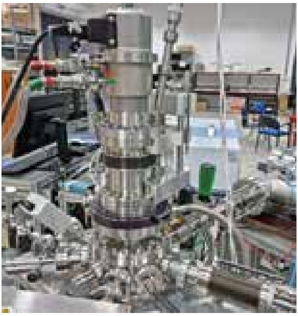
Space Chemistry Laboratories

Facilities for experimentally modelling radiation and thermal effects on astrophysical relevant materials.

Chambers for irradiating astrophysical ice analogues
Two chambers, ICA and AQUILA are part of the Europlanet Research Infrastructure. During the Europlanet 2024 RI project (2020-2024), they provided many transnational access (TA) measurements, extending the capabilities of the ATOMKI Accelerator Centre in the field of laboratory astrophysics and astrochemistry. Both of them were designed to systematically investigate the effect of ion and electron irradiation of interstellar and Solar System ice analogues under UHV vacuum conditions. One of the main goals is to better understand the origin and evolution of the building blocks of life.

ICA – Ice Chamber for Astrophysics/Astrochemistry





The ICA Chamber is a facility for studying the effects of ion irradiation mimicking the galactic cosmic rays and the high energy tail of the solar wind. Ions of different species and charge states from H^+ to multiply charged heavy ions (e.g., S^{6+}) are produced by the 2MV Tandetron accelerator. The ion energy range is 0.2-4MeV for single charged ions, and can go to 10-15MeV for higher charge states. Electrons of 0.5-2keV energy are also available for irradiation. The ice composition at cryogenic temperatures (≥20K), and the physico-chemical changes induced upon irradiation are monitored by infrared spectroscopy. Temperature programed desorption studies may also be performed on both non-irradiated and irradiated ices. The goal is to systematically study space relevant ices under different ion-impact irradiation.

AQUILA – ATOMKI-Queens University Ice-Chamber for Laboratory Astrochemistry

Similarly to ICA, the AQUILA facility is an UHV-compatible chamber equipped with a similar cryogenic sample preparation system, an infrared spectrometer and a quadrupole mass spectrometer. It is predominantly used for experimentally modelling irradiation by solar wind ions. All known components of the solar wind can be produced at the ECRIS Laboratory including highly charged ions. In addition, certain negative ions or molecular ions are also available. AQUILA has been constructed in collaboration with the Queen's University of Belfast and the University of Kent, with the partial support of the Europlanet 2024 RI project.

Other Exeprimental Chambers

- **TOFFEE** a Time-Of-Flight Facility for Extraterrestrial like Experiments designed for measuring the fragmentation channels of space relevant molecules by ion impact on a gas jet target. This way, we can study the primary collision processes, which provide the molecular fragments for the subsequent chemistry.
- **FFTOF** a Field-Free Time-Of-Flight spectrometer for studying the full kinematics of collisions of ions with simple molecules. The results are relevant for understanding planetary atmospheric processes.
- **FROST** Facility for Reliable Optical and Structural Testing is a UHV chamber with cryogenic sample holder, equipped with two lasers and a quarz microbalance for determining the thickness, the density and the optical parameters of the deposited ices as a function of their deposition and thermal history.

REFERENCE

[1] https://spacechem.atomki.hu/

Cyclotron: the Multi-Particle, Multi-Purpose Accelerator

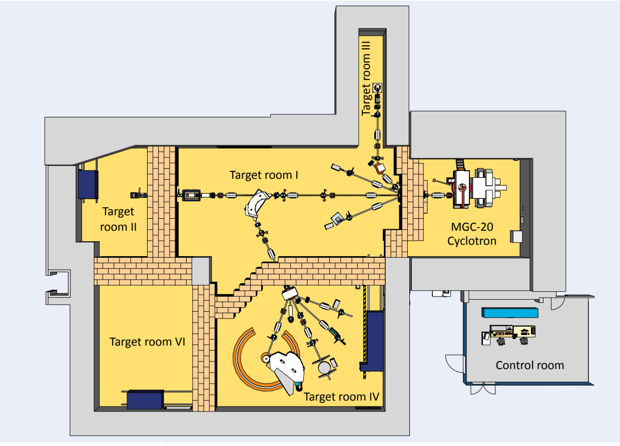
The ATOMKI Accelerator Centre (AAC [1]) presently operates four accelerators. One of them is the cyclotron (type: MGC-20). It produces and can deliver to targets the highest energy ion beams in Hungary, namely 18 MeV protons.

The MGC-20 cyclotron was manufactured in the NIIEFA institute (now St. Petersburg, Russia) and has been in service in Debrecen since 1985. It is a compact isochronous type cyclotron, capable of accelerating the four lightest ions, limited mainly by its internal low-power ion source. The available particles, energy ranges and maximum intensities are in the table.

Ion	**Energy range** (MeV)	**Maximum intensity** (μA)
H^+	2.0-18	50
D^+	2.3-10	50
$^3He^{2+}$	4.0-27	8
$^4He^{2+}$	3.5-20	20

The 18 MeV MGC-20 cyclotron in its vault.

The beam transport system of the cyclotron can deliver beams into 4 different target vaults with a total number of 9 target locations [2]. The layout of the beam transport system is given on next page. The short beamlines in target room I are nowadays intensively used for astrophysical and neutron studies and also for industrial applications. The unique vertical beamline in the basement is dedicated to radioisotope production with high beam power (located below target room I, not shown in the figure). The transport system is also equipped with an analyzing magnet (for targets in room IV), which can decrease the inherent energy spread of the cyclotron beam to the level required by nuclear physics research programs.



Artistic view of the beamline system [2].
The vertical beamline (located below target room I) is not shown.

The cyclotron has a broad range of utilization, from basic research to industrial and medical applications. Many of them are connected to European Transnational Access (TA) applications. Some examples:

- Nuclear reactions of astrophysical relevance are studied using the activation method. Cross sections of many reactions relevant to the astrophysical p-process as well as the $^{3}He(\alpha,\gamma)^{7}Be$ reaction have been measured, which contributed to the better understanding of the investigated stellar processes.
- Thin Layer Activation (TLA) of different machine parts and material samples is performed on an external beam. Stacked foils are irradiated to determine excitation functions and yields of different charged particle induced nuclear reactions and radioisotopes are produced as tracers for different processes.
- Neutron physics, dosimetry research and calibration of neutron detectors are done with quasi mono-energetic neutrons. For radiobiological and radiation hardness studies high-intensity fast neutrons of continuous energy distribution are used.
- Radioisotopes are produced by irradiation and separated by radiochemical methods for nuclear medicine for PET imaging and/or for targeted radionuclide therapy in oncology. Our homemade mini-PET camera helps the newly started agricultural and biological experiments. Some strong gamma emitter radioisotopes are also used in nuclear industry to monitor power plants for leaking.

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[1] S. Biri, et al., The Atomki Accelerator Centre, EPJP **136** (2021) 247
[2] https://youtu.be/a66fMq7ue9A

Fast Neutrons for Basic Science and Applications

Two fast neutron sources are operated at the MGC-20E cyclotron. The radiation transport of neutrons in bulk media, neutron induced nuclear reactions that lead to formation of radioisotopes and the neutron induced damages of irradiated materials are studied.

Quasi-monoenergetic fast neutron source with D_2-gas target

Quasi-monoenergetic d+D neutrons can be produced in the E_n=3–12 MeV neutron energy range via bombarding a D_2-gas target with deuteron beams extracted from the MGC-20 cyclotron. The neutron spectrum and the neutron intensity can be controlled by varying the energy of the bombarding deuterons and their intensity and the pressure of the D_2-gas in the target cell. About three orders of magnitude of the neutron intensity can be covered. A pneumatic rabbit system is available for transporting the irradiated samples between the irradiation site and the HPGe detector of the gamma counting site.

The main applications of the facility are

- implementation of cyclic fast neutron activation methods,
- measurement of cross sections of neutron induced nuclear reactions that lead to formation of radioisotopes,
- integral testing of evaluated nuclear data libraries via the activation technique and via neutron transport measurements (benchmark experiments),
- characterization of neutron detectors via measure ment of their response function as a function of the neutron energy,
- modelling the neutron environments of laser based fast neutron sources,
- radiobiology experiments.

Irradiation of neutron dosimeters with d+D neutrons at the quasi-monoenergetic fast neutron source with D_2-gas target.

Facility with a beryllium target for irradiations with broad spectrum fast neutrons

Broad spectrum neutrons can be produced via bombarding a stopping beryllium target either with proton or deuteron beams extracted from the MGC-20 cyclotron.

The p+Be neutrons can be produced in the E_n=0–17 MeV neutron energy range. Their neutron energy spectrum can be used for modeling the energy spectrum of the atmospheric neutrons and the neutron components of several complex radiation environments (e.g. the low energy part of the onboard neutron spectra of space vehicles and the neutron spectra around high energy physics experiments at high energy particle accelerators).

The d+Be neutrons can be produced in the E_n=0–12.5 MeV neutron energy range and they can be used for modeling neutron environments that are relevant to nuclear energetics.

The neutron spectra and the neutron intensity can be controlled by the energy of the bombarding particles and their intensities. In the case of E_p=18 MeV energy protons the typical neutron intensity is $Y_n=3x10^{11}$ n/s/sr at the direction of the bombarding beam (the $\vartheta = 0^o$ direction).

The main applications of the facility are

- irradiation testing of novel materials, insulators and-semiconductors based photonics and electronics structures and devices developed for applications in radiation environments of space research and high energy physics research,
- radiobiology experiments,
- radiomutation breeding of plants,
- characterization of neutron detectors.

The facility with beryllium target for irradiations with broad spectrum p+Be and d+Be neutrons.

External Beam Line for Industrial Irradiations

The ATOMKI cyclotron can accelerate protons, deuterons ^3He and alpha particles. The energy and intensity values can beseen on the accelerator home page or leaflet. Our beam-line is behind the bending magnet at 22.5°. It has its own high-vacuum system for fast sample changing and vacuum security electronic.

Irradiation facility of external beam to produce radioactive tracers in different machine parts as well as for stacked foil irradiation in vacuum for determination of cross sections and yields of different nuclear reactions.

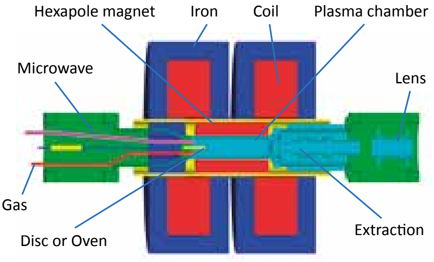
The irradiations are partly performed on an external beam, the beam is extracted through a thin (11 μm) Duratherm© foil. In the case of irradiation in vacuum, the beam extractor unit can be exchanged for a small vacuum chamber, e.g. for stacked foil irradiation. The maximum beam diameter is 2 cm, which can be focused to 0.5 mm. For smaller spot irradiation collimators and masking is requested. The collected charge/beam current is measured by a homemade beam current integrator system. Because of the intensity loss due to beam bending, focusing and collimation, the highest beam current by proton and deuteron irradiations is 2-5 μA, and only 500 nA by ^3He irradiations due to the mixed $^3He/^4He$ gas in the ion source.

The samples were mounted on an x-y table, perpendicular to the beam axis. To make the sample movement more accurate a remote-controlled robotic arm has been installed.

In the case of complicated surfaces and/or high-precision positioning and movements for tens of hours, out of our old x-y table (perpendicular to the beam axis), a recently installed 7-axis robotic arm assures the required accuracy and repeatability. This robotic arm is programable to repeat a series of movements in a loop in order to activate a complicated surface up to the required activity. The movements can be surveilled by a video camera if necessary. In order to achieve proper beam current/collected charge measurement the samples to be irradiated should be mounted in such a way that they are electrically isolated from the supporting elements of the robotic arm. In special cases, when the beam current should be kept low (e.g. by plastic) and/or the cross-section of the desired reaction is relatively low, an irradiation time of several tens of hours is requested. The sample movement and the positioning should be reproducible and stable even in such cases. The devices within the target hall and especially in the vicinity of the beamline were selected cautiously in such a way that they do not contain radiation-sensitive electronics.

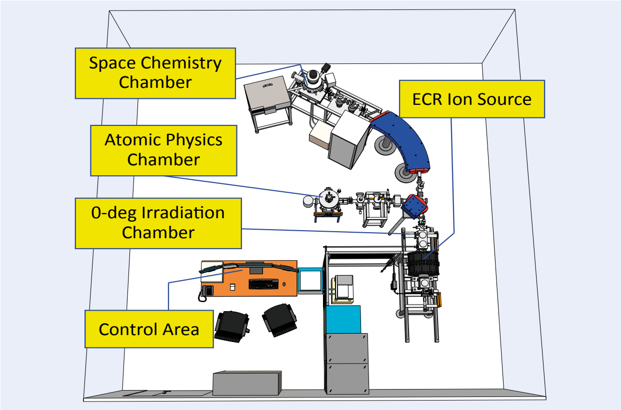
The Electron Cyclotron Resonance Ion Source (ECRIS)

The ATOMKI Accelerator Centre (AAC [1]) presently operates four accelerators. One of them is the ECR Ion Source which has been operating in ATOMKI since 1996. Instead of the usual application of such sources, this homemade facility does not deliver ion beams for a high energy accelerator, but provides various low energy ion beams and plasmas for atomic physics and radiation driven space physics research, for plasma investigations and for material science.



The ATOMKI-ECRIS, cutaway view.

An ECRIS is a plasma source, an ion source, and a particle accelerator in one. It produces atomic plasma from which positive or negative ion beams can be extracted to be transported to a target. The plasma (heated by microwave in the GHz region) is confined in the plasma chamber by magnetic field which is produced by the combined usage of hexapolar permanent magnet and solenoid coils. Due to the effective energy transfer from the microwave to the plasma electrons, this ECRIS can produce reasonably high charge state of ions. For example, fully stripped Ne ions, He-like argon (Ar^{16+}) and 30-times ionized gold beams were generated. Proton beams and multiply charged ions of He, C, N, O, Ne, Si, Ar, Kr, Xe are used in daily routine with high intensity. Due to the high ionization efficiency and based on the several vaporization techniques available in the laboratory, this ECRIS can produce ion beams from a variety of solid materials like Ca, Au, Ag, Fe, Ni, C_{60}. It was also proved that besides highly charged positive atomic ions H^-, O^-, OH^-, O_2^-, C^-, C_{60}^- negative ions and H_2^+, H_3^+, OH^+, H_2O^+, H_3O^+, O_2^+ positive molecular ions can also be generated with appropriate intensities. The kinetic energy of the extracted ion beam can be varied between 50 eV and 900 keV, depending on the extraction voltage and on the charge state of the accelerated ion species.



The ECRIS Laboratory [2], main devices labeled.

The application of the ECRIS covers several different fields, many of them are connected to Transnational Access (TA) projects. In the Atomic Physics Chamber classical atomic physics research are carried out. Transportation of the highly charged ions through micro-capillaries or time-of-flight spectra of fragmented species of molecule-ion collisions are investigated. In the new Space Chemistry Chamber radiation induced processes taking place in space are studied in laboratory environment. Ices deposited at 20-70 K temperature made of special gases (or from a mixture of gases) are irradiated with proton, oxygen, sulfur, carbon and other ion beams. The chemical changes of the ices are monitored by IR and QMS spectrometers before, during and after irradiation. The question to be answered is: how new molecular compounds are created in space? The ECRIS is frequently used as an ordinary implanter. Using the extremely wide element and charge choice, medical, industrial samples or even meteorite slices are irradiated in special small chambers. The samples functionalized this way are then analyzed in other laboratories. Since this ECRIS is not connected to any post-accelerator, it is an excellent device for plasma physics studies. The RF, X-ray and visible light radiation emitted by the plasma are investigated. They mirror back essential information on the plasma parameters opening the possibility to optimize the plasma conditions over the source operation. One of the main question to be answered is: what is the origin of the plasma instabilities (strongly destroying the ion beam properties) and how to suppress them?

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[2] https://youtu.be/GyKDXKKK8SQ

Stable and Clumped Isotope Mass Spectrometry

Stable and clumped isotope analysis in the service of study of past- and present-day geo-, hydro- and biosphere.

The stable and clumped isotope infrastructure can carry out stable isotope analyses by a Thermo Finnigan Delta plus XP and Delta V Plus isotope ratio mass spectrometers (IRMS), specially designed for stable isotope ratio measurement of five elements (S, C, H, O, N) in gaseous form. The IRMSs are equipped with several sample preparation devices (including a coupled TC/EA, EA, Automated Carbonate Digestion and a couple Gas Bench system) in order to transform the sample into gaseous (H_2, CO_2, CO, N_2, SO_2) form.

The infrastructure has also a Thermo Scientific 253 Plus 10 kV high resolution isotope ratio mass spectrometer which is able to measure conventional stable isotope ratio ($\delta^{18}O$, $\delta^{13}C$) of small amount of carbonate samples down to 30 µg. The 253 Plus 10 kV IRMS is dedicated to analyses of clumped isotopes compositions (Δ_{47}) of carbonates in gaseous form. It has a KIEL IV automatic carbonate device which consists of a thermostated reaction region, with an acid bath for conversion of carbonates to CO_2, a trapping and gas cleaning system, and a microvolume inlet system. This system is suitable for measurement of traditional carbon, oxygen isotope ratio of small (down to 30 µg) carbonate samples besides the determination of clumped (Δ_{47}) isotope ratio on samples of 1.3-1.7 mg.

Clumped isotope mass spectrometry
(253 Plus high resolution isotope ratio mass spectrometer equipped with a KIEL IV carbonate extraction device).

Isotope ratio (IR) analysis of carbonate samples is increasingly important in palaeoclimatic reconstructions and geochemical research. Moreover, IR analysis of small carbonate samples is also a priority study area (e.g., foraminifera, bivalves, brachiopods, otoliths, corals, biospheroids, speleothems). At ATOMKI, with a sample size of >300 µg for the DELTA V Plus or >30 µg for the 253 Plus, we can achieve an overall precision of 0.04 ‰ for $\delta^{13}C$ and 0.08 ‰ for $\delta^{18}O$. Clumped isotope thermometry, in contrast to the traditional method, examines the relative excess in binding of the ^{13}C and ^{18}O isotopes in the lattice structure. This shows a significant temperature dependence. However, since the abundance of the chemical bond between ^{13}C and ^{18}O is extremely rare, high precision measurements are required to determine it (long-term reproducibility 0.025-0.035 ‰).

On-line IR analysis of organic samples (soil, bone collagen, cellulose, etc.), for $^{13}C/^{12}C$, $^{15}N/^{14}N$ and $^{34}S/^{32}S$ at ATOMKI is carried out by using a conventional Elemental Analyzer – continuous flow IRMS. The TC/EA coupled to IRMS is used for on-line analysis of $^{18}O/^{16}O$ and $^{2}H/H$ ratios of organic and inorganic samples.

Measurement of $^{2}H/H$ and $^{18}O/^{16}O$ ratios of water at ATOMKI is carried out on IRMS attached to sample preparation device or on laser spectroscopes and is used from applications and studies on natural isotope abundance in the hydrologic cycle, through authenticity control on beverages to metabolic studies.

Close up view to the autosampler of
the GasBecnh-II carbonate extraction device.

Radiocarbon Competence Center (INTERACT)

New and efficient sample preparation devices for radiocarbon studies and high-level training regarding the measurement technology.

Since its Nobel Prize-winning discovery in 1960, the radiocarbon (C-14) dating method has expanded far beyond archaeological applications. It has become an indispensable tool in complex environmental, geological, hydrological, meteorological, and climatological studies. Nowadays, this isotope is also used in drug development, medical research, and nuclear environmental protection.

At ATOMKI, research and method development based on radiocarbon measurements have a history of more than 50 years. One of the major milestones of development was the installation of a MICADAS type accelerator mass spectrometer (AMS) in 2011, jointly with the Isotoptech Zrt. Today, an internationally outstanding and high-profile AMS laboratory has been established in Debrecen. The theoretical and technical knowledge acquired jointly by the two parties and the joint laboratory gives a perfect basis for the establishment of an internationally competitive AMS C-14 competence centre [1, 2].

Latest generation LEA AMS (Ionplus AG) system at ATOMKI.

Based on the scientific background and professional staff together with the equipment development and manufacturing experience of the Isotoptech Zrt., a knowledge transfer center promptly adapting to the worldwide rapidly expanding AMS C-14 analytical demands may be established, which is able to serve the recent research approaches and the demands of the market [3, 4].

Establishing analytical approaches at ATOMKI, necessary for C-14 dating, industrial applications, C-cycle study and environmental research. ATOMKI is the only institute in Hungary having AMS C-14 analytical methods for national and international collaborations and research [5].

Gas Ion Source Interface of LEA for < 0.1 mg sized C samples.

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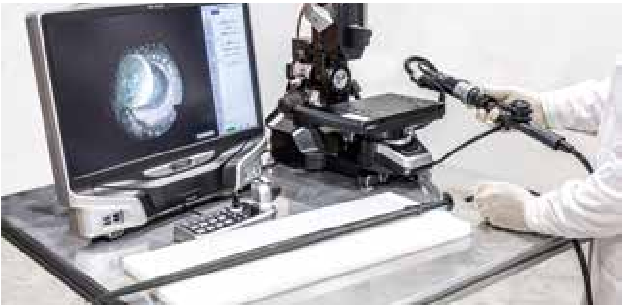
Laboratory for Heritage Science

Information on the structure and material composition of objects over a wide range of sizes is obtained through imaging and analytical techniques that allow material examination at the microscopic level.

Heritage science is a relatively new term for the complex research on our cultural and natural heritage, encompassing heritage management, analysis, conservation, interpretation, and documentation. In addition to archaeology, museology, art history, anthropology, and palaeontology, methods coming from the natural sciences, such as sensitive analytical procedures, play a major role in the discipline. The Laboratory for Heritage Science was founded to promote research in the field of cultural and natural heritage in collaboration with national and international partners. The laboratory is equipped with the following devices:

Digital 3D microscope: The first step in the investigation of cultural heritage objects is optical imaging. Besides the image, the digital 3D microscope yields quantitative information about the structural features of the object not only on a horizontal but also on a vertical scale. This is useful, for example, for determining the depth of carvings or the height of reliefs.

Micro-XRF equipment: It is a tool for sample characterization using small-spot micro-X-ray fluorescence. The measurement gives quantitative information about the composition and distribution of elements. The spectrometer is optimised for high-speed analysis of points, lines, and 2D area scans (element mapping) of the samples. It works both in vacuum and in air and has a large chamber.



Examination of a Bronze Age sword with a digital 3D microscope.

Scanning electron microscope: It scans a focused electron beam over a surface to create an image. The electrons in the beam interact with the sample, producing different signals that can be used to obtain information about the surface topography and composition. The device also operates in a low vacuum.

Raman microscope: In the case of Raman spectroscopy, the vibration spectrum can be used to obtain information on the type, position, and orientation of the functional groups in molecules. The compounds can be identified by their characteristic Raman spectra.

All the listed techniques are non-destructive and are offered for interdisciplinary research. Projects from national partners (museums, universities, research institutions) are carried out within various frameworks, especially within the **E-RIHS.hu** initiative, which aims to establish the Hungarian node of the European Research Infrastructure for Heritage Science. In addition to projects on art and archaeological objects, the laboratory also enables research in the fields of materials science, biology, atmospheric aerosol research, geology, etc.

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Micro-XRF spectrometer in the Laboratory for Heritage Science.

Complex Sample Analysis in the Field of Materials Science

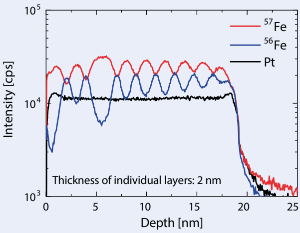
In ATOMKI we offer we offer a wide range of surface analytical techniques for both physical and chemical characterization of materials. Various sample preparation methods exist for deposition of thin films and multi-layered structures.

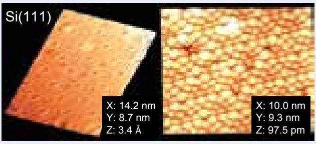
The activity of the institute in the field of materials science covers the composition and structure analyses of different samples. Instruments and methods available in our laboratories – *e.g. depth profile analysis by mass spectrometry (SNMS), determination of chemical states by photoelectron spectroscopy (XPS), low-energy ion scattering spectroscopy (LEIS), focused ion beam scanning electron microscopy (FIB SEM), scanning probe microscope (SPM) and X-ray diffraction (XRD)* – make material analyses possible for a broad range of applications. For example, we can perform bulk composition as well surface analyses of samples or analyze the additives and doping materials. A complex analysis of thin layers or layered structures can also be performed by measuring e.g. their thermal stability, variation of phase and/or chemical composition in depth, quality of the interfaces. It is also possible to determine e.g. the crystal structure, the crystalline/amorphous phase ratio, or the residual stresses in various types of materials, the quality check of industrial products and study of surface layers, corrosion on surfaces, surface coatings, etc. Possible application fields include quality check of industrial products and investigation of surface layers, corrosion, stability of surface coatings etc. The results provide feedback which improves the quality and/or decreases the number of faulty products on the production lines.

In our laboratory we use magnetron sputtering techniques to produce metallic and semiconducting type of thin films or multilayers with 2-3 nm individual layer thicknesses. Oxide surface controlled thin films can be deposited by plasma enhanced Atomic Layer Deposition (ALD) system. The method allows us to deposit thin films precisely, layer by layer, even one atomic layer. By Secondary Ion/Neutral Mass Spectrometry (SIMS/SNMS) and other standard sample analysing techniques which are also available in our institute (e.g. X-Ray Diffraction, Scanning and Transmission Electron Microscopy, Electron Spectroscopy or Scanning Probe Microscopy for surface morphology analysis in atomic level), we can perform a complete analysis of the thin layers/multilayers in order to determine the sample composition with high depth resolution (~1 nm) or lateral distribution.

For example, with depth profiling method we identified a defect that occurred the during preparation of the ^{56}FePt/^{57}FePt multilayered structure, which was only possible with this isotope sensitive method. This mistake in multilayer sequence fully destroyed the giant magnetic resistance property of the sample.

We can determine the chemical state of the surface and interface layers of the nanostructures, which can be obtained by X-ray induced photoelectron and Auger spectroscopy methods (XPS, XAES). In-depth concentration profiles of surface components can be derived removing the surface layers successively using low energy (<keV) ion sputtering in the case of thin (< 100 nm thickness) and ultrathin (< 5-10 nm thickness) layers, eg. passive layers of reactor components, thin film structure solar cells or semiconductor devices.





Identified layer thickness defect accrued during preparation of ^{56}FePt/^{57}FePt giant magnetic resistance (GMR) multilayers.

Atomic resolution surface reconstruction image of Si(111) made by scanning probe microscope (SPM) equipment.

Noble Gas Mass Spectrometry

A VG5400, a MM5400 and a Helix SFT mass spectrometers are used in isotope hydrology and noble gas geochemistry.

Noble gas mass spectrometers are essential tools in isotope hydrology as well as in geochemistry. Determination of tritium and dissolved noble gases in environmental water samples can be precisely determined by dedicated mass spectrometers. Tritium (^3H), $^3H/^3He$ apparent age, noble gas recharge temperature, $^3He/^4He$ isotope ratio contribute to understanding what has happened in the aquifer in the past and present.

Accurate and sensitive ^3H analysis can be performed by the ^3He-ingrowth method. Water samples are first distilled, and then poured into stainless steel containers. The dissolved gases including helium are pumped away by vacuum pumps. Several weeks later, the decay product of tritium, ^3He is determined by a Helix SFT noble gas mass spectrometer.

To improve the mass spectrometric measurement, a pure ^4He spike is added to each sample during the admission to the preparation line [1]. The detection limit is 0.01 TU or even better, if longer storage time is used.

VG5400 noble gas mass spectrometer.

Dissolved noble gases can be used to determine recharge and discharge processes. Neon, argon, krypton and xenon amounts are determined by the isotope dilution method: a well-known amount of ^{21}Ne-^{38}Ar-^{86}Kr-^{126}Xe isotope mixture is added to each water sample during preparation.

Tritium and noble gas measurements allow us to calculate $^{3}H/^{3}He$ apparent ages. The recharge temperature, the excess air components as well as the tritiogenic ^{3}He component can be decomposed from the measured noble gas concentrations and $^{3}He/^{4}He$ ratio.

Stainless steel containers to store water samples for ^{3}He production.

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Neptune PLUS MC-ICP-MS

A mass spectrometer to determine accurate isotope ratios of different elements in environmental geochemistry, and uranium-thorium dating of carbonates.

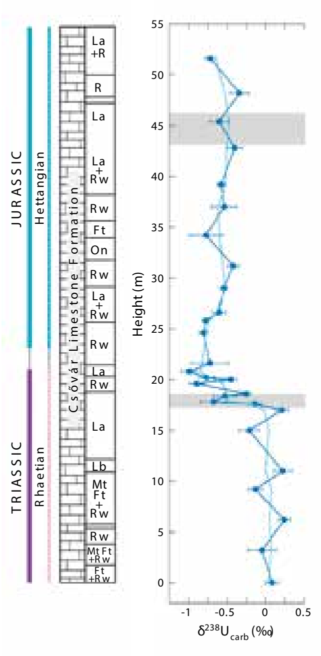
In 2019, a Neptune PLUS multicollector ICP-MS (Thermo Scientific) was installed in the institute. Non-conventional isotope ratios as well as $^{234}U/^{230}Th$ dating of speleothems and freshwater carbonates are determined with high accuracy. The chemical preparation of the samples are performed in a clean laboratory of Class 1000.

The detector configuration allows us to use six and three Faraday collectors with 10^{11} and 10^{13} Ohm resistors, respectively, and a SEM (secondary electron multiplier) for sensitive analyses of tiny ion intensities. The instrument is equipped with two Aridus3 desolvating nebulizer systems. To avoid cross contamination, one nebulizer is used for U/Th dating of carbonates, while the other one is used for analysing other isotope ratios.

For U/Th dating, a triple spike is used, which has been prepared from an IRMM-3636a double spike solution mixed with an SRM4328C ^{229}Th reference material. The internal calibration of the mass spectrometric measurement of uranium as well as thorium is performed with an internal mixture prepared from a CRM-112A uranium standard solution and the IRMM-3636a double spike solution.

Geochemical applications involve $^{87}Sr/^{86}Sr$ isotope ratios of rock, groundwater, environmental and archaeologic samples, as well as lead, uranium, iron, copper, hafnium, silicon, magnesium and calcium isotope analyses.

As an example of the capability of the accurate isotope analysis, $\delta^{238}U$ values of a limestone sequence are presented on the figure. The uranium isotope dataset from the Triassic-Jurassic boundary (TJB) section of Csővár, Hungary shows a major negative anomaly (Somlyai et al., 2023). The abrupt and major $\delta^{238}U$ decline from -0.39 to -0.93 ‰ before the TJB suggests a rapid increase in the global extent of bottom-water anoxia and confirms the observations and findings of the previous $\delta^{238}U$ study across the TJB. This anomaly coincides with the previously detected carbon isotope anomaly, which is associated with the first, major intrusive phase of the Central Atlantic Magmatic Province activity and marks the extinction horizon.



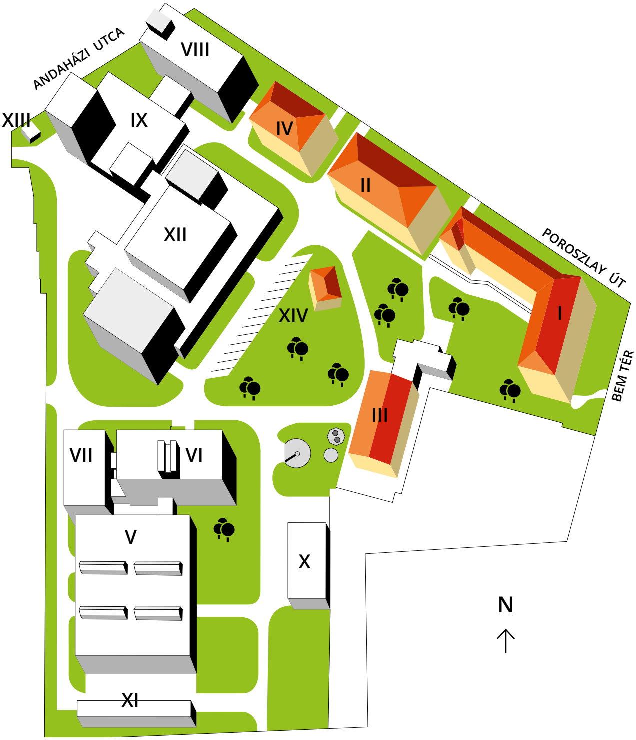
Uranium isotope data from the Csővár section (ETE refers to the end-Triassic extinction).

The measurements were performed using the Neptune Plus MC-ICP-MS. Results were calibrated using the international standard synthetic reference material CRM-112A. Each sample has been measured a minimum of three times with standard-sample bracketing. Analytical errors of measurements range from 0.02 to 0.12 ‰ (±1σ) which is consistent with the analytical errors of previously published uranium isotope data. To assess the external reproducibility, we measured modern seawater samples with reported uranium isotope values. These samples underwent column chemistry in the same manner as the limestone samples. The modern seawater standard gave a mean $\delta^{238}U$ value of -0.409±0.029 ‰, which is in agreement with the previously published value of -0.39±0.01 ‰.

REFERENCE

[1] A. Somlyay, et al., Earth Planet. Sci. Lett. **614** (2023) 118190

Map and Contacts



CONTACTS

Address: **Hungary, 4026 Debrecen, Bem square 18/c**

Postal address: **Hungary, 4001 Debrecen, P.O. Box 51.**

Telephone: **+36 52 509 200**

Telefax: **+36 52 416 181**

Email: **titkarsag@atomki.hu**

GPS: **N47.544116,E21.624160**

https://atomki.hu

European laboratory
for accelerator based
sciences